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ABSTRACT

This is the final evaluation report of the On Growth and Form (OGAF): Learning Concepts of Probability and Fractals by Doing Science project that aimed at engaging high school students in hands-on science activities, experiments, and computer simulations that use probability and fractal geometry to model ragged structures in the real world. Formative evaluation techniques were employed which included content inspection of program materials by experts, pilot tests with small numbers of students, and field tests with larger numbers of students and teachers. Other data collection techniques included formal interviews with project participants, informal conversations and analysis of project documents. This report includes the following sections: overview of the OGAF project, evaluation plan, description of final OGAF units, experiments to accompany OGAF units, strategies for program monitoring and evaluation, findings from initial formative evaluation, field trials in area high schools, impact on teaching and learning, effects on participating teachers, the promotion of interdisciplinary science and mathematics, effects on other participants in the development process, the model of development--lessons learned, the future of OGAF--The future of high school science, and dissemination. (JRH)

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ED 391 670

CURRENT INTERDISCIPLINARY SCIENCE RESEARCH IN THE HIGH SCHOOL CLASSROOM

FINAL EVALUATION REPORT

for

ON GROWTH AND FORM: Learning Concepts of Probability and Fractals by "Doing Science"

Prepared for the
National Science Foundation
Grant Numbers: MDR-8955041 and MDR-91123001

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With contributions from
Melissa Erickson, Linda Shore, Edwin Taylor, and Paul Trunfio

Fall, 1995

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CURRENT INTERDISCIPLINARY SCIENCE RESEARCH IN THE HIGH SCHOOL CLASSROOM

FINAL EVALUATION OF "OGAF"

On Growth and Form: Learning Concepts of Probability And Fractals by Doing Science

A. Overview of the OGAF Project

OGAF is the acronym for *On Growth and Form: Learning Concepts of Probability and Fractals by Doing Science*, a project funded by the National Science Foundation through its division on Applications of Advanced Technology. Additional support has been given in the form of equipment grants from Apple Computer Corporation, Digital Equipment Corporation, International Business Machines, and Silicon Graphics, Inc.

A.1 OGAF Project Goals

The OGAF Project seeks to engage high school students in hands-on activities, experiments, and computer simulations that use probability and fractal geometry to model ragged structures in the real world. Students develop the concept that chaotic, random behavior at the microscopic level can give rise to ordered, predictable behavior at the macroscopic level. By experiencing the same modeling techniques employed by scientists, students should develop inquiry skills like those of practicing scientists. Thus, current science is used as a vehicle to motivate student learning, address student preconceptions, and give students a chance to engage in scientific research as it is actually practiced. Special attention is made to make the materials appeal to females and minorities.

A.2 The Development Team

The OGAF education development project joined the efforts of university science professors and professors of education, visiting international research experts, high school science and mathematics teachers, graduate and post-doctoral students in science, mathematics, and education, undergraduate students in science, engineering, computer science, education, art and film, as well as high school science and mathematics students. The nucleus of the development team included: the Principal Investigator/Project Director who is Professor of Physics, and Director of the Polymer Center at Boston University; a second senior scientist with considerable experience in the field of education who served as co-director; an experimental physicist who led the development of experiments yielding patterns in nature which comprise the hands-on compliment to the OGAF computer simulations; a post doctoral fellow who did his Ph.D. thesis on the application of random walks to polymer science; a program manager with a background in physics, engineering, and computer science who provided technical and administrative support to the project; Ph.D. students engaged in current research on fractals, polymers, and DNA; and undergraduate programmers who were guided by the post doctoral fellow, co-director, or project manager, depending on what they were programming, and when they held the assignment. The professional staff reported to the Project Director.

A.3 Scope of the Project

Research by participating scientists provided the educational focal point for the OGAF Project: the growth and form of fractal patterns in nature. Applications of these concepts span many scientific disciplines, including physics, chemistry, biology, and environmental science. Areas of mathematics which are taught and reinforced in the projects include probability and statistics, scaling, logarithms, and fractal geometry. Six modules were developed, three of which saw extensive pilot testing, field testing, and further revision. Each module consists of a cycle of (1) student prediction activities, (2) hands-on activities and experiments followed by (3) computer simulations. Pairing laboratory experiments with computer simulations challenges students to engage multiple representations of concepts as they study the effects of manipulating variables.

A.4 Scientific and Educational Importance

The traditional science curriculum used in most American high schools today includes little mention of recent scientific advances. For most students, the term "modern science" refers to quantum mechanics, nuclear science, atomic theory, relativity, and Darwinian evolution -- all a half century old or more. Research scientists at the Polymer Center at Boston University have been collaborating with post-doctoral research workers, graduate students, high school teachers, undergraduate programmers, and educational researchers in the development of interdisciplinary materials that deal with current scientific research topics which can be infused into the traditional high school science and mathematics curriculum. The materials are inquiry-based, favoring student-driven experimentation over lecture-based instruction. The approach is designed to teach students what science is--inquiring, experimenting, and developing new theories, rather than listening to people talk about what has been done and repeating old experiments.

The computer plays a central role in this approach which focuses on modeling and testing observed phenomena. Recent advances in computer technology provide the power of mainframe systems in relatively compact and inexpensive personal computers which will become generally available over the next decade. The group at Boston University has been working toward harnessing this new technological resource as a tool for teaching high school students. The OGAF approach not only allows students to learn truly new topics in science but also engages students with tools which are similar or identical to those that practicing scientists use.

B. Evaluation Plan

B.1 Audiences To Be Served

The primary audiences to be served by this evaluation report include: the project directors and the professional staff of the OGAF Project team; their international network of colleagues in science education and the sciences who were consultants and advisors on the project; the high school teachers who worked closely as integral members of the OGAF team throughout the course of the project; and members of the NSF Science and Engineering Education Directorate, particularly those representing the section on Applications of Advanced Technology that oversaw the funding and monitored the progress of the project.

Other important audiences who may be interested in the report are other NSF project directors/principal investigators who are the recipients of other grants for educational research, innovation, and development in science education; other science and education faculty members and administrators at Boston University and other institutions of higher education who wish to consider both the benefits and the requirements for this project of collaborative work; and especially high school science and mathematics teachers who are prospective users of these applications of advanced technology to effective teaching and learning in science and mathematics at the high school level. The latter may be reached most effectively through their professional associations. Scientists in government, industry, and the military may be interested as well.

B.2 Scope of Work and Approaches to Evaluation

The Project Director contacted the evaluator in the Spring of 1989 and asked her to review the initial proposal and provide feedback, especially on the section pertaining to evaluation. When the grant was awarded later that Summer, he sought her assistance in getting the project underway, starting with meeting and interviewing potential staff members. He had never engaged in educational development work, nor had he worked with schools before, so he requested her assistance in securing sites for the project. She had urged him to bring high school teachers on board, right from the start. We started by using a network of contacts in science education to identify outstanding teachers who would be receptive to innovation and willing to find room for OGAF materials and units in their high school courses.

Especially in the early phase of the development of each OGAF program and unit, the developers needed timely feedback so that they could use the information to make the necessary revisions. Therefore, the evaluator employed formative evaluation techniques which included content inspection of program materials by experts, pilot tests with small numbers of students, and field tests with larger numbers of students and teachers, each step providing immediate feedback to the developers who would use the information to make necessary revisions. Program officers and monitors from the National Science Foundation also wanted to know whether this highly innovative model of collaborative program development might be replicated at other universities.

The evaluator regularly visited the computer laboratory facilities, offices, and the science laboratory which were principal sites for the development work. She also attended weekly project meetings and received all e-mail correspondence directed to the senior administrative staff.

The evaluator's official commitment to the project was one month's equilavent effort for each of the five years the project was funded. She was able to extend her contact with OGAF classroom trials and development work by serving as mentor to a young woman employed full-time as a research assistant on a related grant to conduct research on teaching and learning with OGAF. This association kept the evaluator up to date with day to day workings of the project while it afforded her the opportunity to guide the research assistant in her observation and analysis of classroom practice with OGAF.

In addition, the evaluator conducted one or more formal interviews with almost every participant in the project, including the project directors, all senior staff members, consulting faculty from science education, several international consultants, all of the master teachers, many of the graduate students, and the undergraduate programmers as well. These formal interviews were supplemented by on-going informal conversations with faculty members and graduate student participants in the project, and participant-observation in staff meetings. Finally, project documents, proposals, and reports generated by the project also served as sources of data about the project. The strategies used for program monitoring and evaluation are described more fully in Section E of this document.

B.3 Limitations and Constraints

As the OGAF project matured, and master teachers were about to use selected units in their classrooms for the second time, the evaluator urged that she and some of the scientists work with them on the creation of performance assessments which could serve as evidence for what students were learning from the use of OGAF materials. But the project budget would not permit additional consulting time with teachers during the summer of 1993 and 1994, so a transition to a more summative approach to evaluation using new performance assessments could not be made. What's more, some of the units created later in the five-year span of the project still needed formative evaluation for product revision.

The evaluator was employed for one month's equivalent time each year of the five-year OGAF project. She distributed this time and more over the course of the calendar year, but with full teaching responsibilities at Boston University, she was not always able to spend time at the three field sites schools when those classes conflicted with her own teaching schedule at the University. She did observe each of the master teachers and their students using OGAF on several occasions. Due to compatible scheduling, she was able to spend more than 100 hours (including every Friday from 8:00 a.m. to 4:00 p.m. for three months) at one of the field sites when OGAF was being used intensively in two science and two mathematics classes, the former with double laboratory periods.

B.4 Related Work on Another Grant

Budgetary constraints and constraints on the evaluator's time and availability were alleviated by the opportunity to collaborate with individuals who were part of another grant to the Boston University Science and Mathematics Education Center which was funded by the National Science Foundation to conduct Research on Teaching and Learning (RTL) with OGAF. The RTL grant supported a full-time principal investigator, a noted cognitive psychologist who served as a consultant to the OGAF project, and three graduate students in science and health education. The graduate students spent considerable time observing and taking ethnographic field notes in OGAF classrooms at the three field sites. The evaluator collaborated with these individuals in arranging case studies of minority students, designing interview protocols and questionnaires, collecting data, exchanging information, and corroborating findings gained from field visits.

C. Description of Final OGAF Units

The OGAF units focus on the growth and forms of fractal patterns in nature, a theme which underlies the current research and publication of active scientists in our group. The units engage high school students in experiments and other hands-on activities as well as computer simulations that use probability and fractal geometry to model the ragged real world. Examples of fractal patterns in nature abound; they include lightening bolts, river deltas, coastlines, and mountain ranges. Nerve cells, termite tunnels, bacteria cultures, and root systems are also examples of fractals. So too are galactic distributions, forest growth and burning, lungs, the nervous and cardiovascular systems, and even cauliflower and broccoli.

Constructing models of the growth of fractal patterns starts with coin flipping and a few simple rules. The students flip coins, execute the rules, compile group results, and make predictions about the outcomes, slowly building models of a few structures. Then they use the computer to effect high speed coin flipping, building a flood of model structures. Several units have been developed, field tested, and refined. Each module consists of a cycle of hands-on activities and experiments, followed by student prediction activities, and finally computer simulations to model the patterns and phenomena. The programs enable students to model the fundamentally random microscopic processes that lead to predictable structures in nature.

Some teachers like to use simpler programs first, like those on probability and randomness, and then progress with their students to more complex applications like the modeling of coastlines, the determination of fractal dimension, and the study of diffusion limited aggregation. Each random structure produced by the student is unique, yet each is an example of a class, whose common features emerge after many repetitions. The student varies several parameters to explore the immense variety of structures that can emerge, comparing these computer generated structures with images scanned from simple laboratory experiments. Students also vary experimental conditions and compare resulting structures with the models.

Scores of programs have been considered throughout the five-year period of development in the OGAF project. As greater sophistication in programming, clearer vision of how the programs might be infused throughout the present high school curriculum, and with benefit of field testing for many of the programs, the team decided to focus their finishing efforts on a smaller number of programs distributed across seven units. The first unit explains basic theories concerning randomness and probability. Subsequent units address the role randomness plays in pattern formation as well as characteristics of fractal forms. Each unit includes one or more hands-on activities, experiments and computer simulations. Table 1 provides an overview of each of these components for each of the OGAF units. The following account of the final units of OGAF materials and programs is adapted from Trunfio (1995), updated from Erickson (1993).

C.1 Random Walks Unit

This unit introduces students to basic ideas about randomness. Components explain probability theory as a means to analyzing random events, and how predictable results at the macroscopic level can grow out of microscopic random processes.

Hands-On Activities

Lottery- Students flip coins until they get three heads in a row. When they get three heads in a row, they predict the outcome of the next flip using one of three alternative strategies: "On a Winning Streak," "Running Out of Luck," or "Random." Students repeat this process a number of times. After several trials, students compare the success of their strategy with the alternative strategies employed by their classmates.

Coin Flipping- Students predict the outcome of flipping a set of ten coins 1000 times. How many times would all ten coins come up heads? How many times would nine coins come up heads? etc. Then students flip coins for themselves and average results over the entire class.

Random Walks- Students are given a number line and a walker. Students place the walker in the center of the number line and move it left or right depending on the outcome of a coin flip.

Galton Quincunx/Pascal's Triangle - One of the simplest and clearest demonstrations of probabilistic phenomena is produced by dropping balls over an array of pins. By being forced to go either left or right, the balls form a normal distribution in the catch bins at the bottom of the array. Repeated trials demonstrate a number of phenomena: averaging; statistical variation; etc. The combination of an actual physical model with the computer simulation that can then run many trials rapidly reinforces the fundamental probabilistic notions employed throughout OGAF.

Experiments

The Diffusion Chamber- Two different gases are inserted at the opposite ends of a clear glass tube. (Typically these gases are NH_3 and HCl). The gases diffuse through

Table 1. Overview of OGAF Units

Unit Titles	Hands-On Activities	Experiments	Programs
1. Random Walks	Lottery Coin Flipping Random Walks Pascal's Triangle	Diffusion Chamber Diffusion in Gels Liesegang Rings	Lottery Random Walks Anthill Deer Many Walkers Diffusion Chamber Roulette DNA Walk
2. Fractal Dimension	Fractional Dimension Testing Log Plots Coastline Measuring	Bacterial Colony Morphologies Termites	Fractal Dimension Fractal Coastline
3. Aggregation	Pattern Building	Electrochemical Deposition Hele-Shaw Roots Greased Lighting Crystallization Cracks/Erosion Dielectric Breakdown	Fractal Dimension Aggregation Kit Chill Out Spiral Galaxy Structure
4. Disordered Systems	The Chaos Game	Resistor Network	Gasket Meister The Iterator
5. Rough Surfaces	Paper Tearing	Paper Wetting Image Analysis	Surface Analyzer 2-D Random Walk
6. Fractal Noise			Fractal Music

Source: Trunfio, 1995.

the tube and when they meet they form a white dust (NH_4Cl) part way along the tube. Students are asked to predict mathematically where the "dust" will form and how soon this will occur.

Diffusion in Gels-Two rectangular slabs of gelatin, agar, or some other gel are placed in contact. One is clear gel. The other has concentrated food color added. Over a period of a few days students watch and measure the diffusion front of color as it moves through the clear gel into and through the clear gel.

Liesegang Rings - A crystal of copper sulfate is placed in the center of a gel containing dissolved potassium chromate. As the copper sulfate diffuses into the gel, copper chromate crystals precipitate out, creating a colored ring. Locally this depletes the chromate below the precipitation threshold. The copper must diffuse further to find chromate concentration above the precipitation threshold. As this process repeats, the result is a set of colored rings, developing in time, that illustrate diffusion.

Computer Programs

Lottery - Designed to confront misconceptions about "winning streaks" and the predictability of random events. This program flips coins until it gets four heads in a row. When fours heads in a row occur, the computer stops and allows the student to predict (bet) what the result of the next flip will be. The computer keeps track of the student's "score" by recording the number of times they correctly predict the next flip.

Random Walks - This program demonstrates how order can grow from randomness. There are three parts to this program. *Coin Flipping* allows the student to flip a set of ten coins a large number of times quickly and summarizes in the form of a histogram the number of heads resulting from each trial. In *Random Walks* the direction of the next step of a one dimensional random walker is controlled by the flip of a coin. Where the walker lands at the end of ten steps is compiled in a histogram at the bottom of the screen. The direction a ball moves over each peg in a *Pascal's Triangle* is also controlled by a coin flip. In this case the histogram bars show where each ball exits the last row of pegs.

Anthill- This program allows the student to experiment with multiple two dimensional walkers. A large number of "ants" (walkers) start together in the center of the computer screen. Each ant moves independently, in a random walk, and the area covered by the ants grows. The student may change the relative probability that each ant moves in each direction: north, south, east, or west.

Deer- The two dimensional random walkers in this program are deer. The deer move around a field of grass that they eat. The lives and movements of these deer are governed by a number of rules. How big are the deer? How old are the deer when they reproduce? How many steps can a deer take without food? Also, how long after it is eaten does the grass grow back? All of these variables are controlled by the student, who realizes that more variables than a coin flip are at play when a random walk takes place in nature. The computer illustrates in the form of a chart the population of the deer and the amount of grass in the field. The goal? To get a stable population where neither the deer nor the grass overrun the field.

Many Walkers- Many one dimensional random walkers are displayed in a vertical column. Each walker moves independently and after each step the computer displays a histogram of walker locations. The computer also displays the average value of X, where X is the displacement of walkers away from their initial position. Also shown is a graph of average X^2 vs. the number of steps; in the limit of a large number of walkers, this graph approaches a straight line, a fundamental consequence of random walks

Diffusion Chamber- This program demonstrates how molecules of two different substances starting at opposite ends of a tube diffuse along the tube in random walks. A white precipitate forms where the substances meet each other. The student controls the length of the tube and the step size of each substance to see the consequences for the location and speed of formation of the visible precipitate.

Roulette- This program introduces the student to the method the computer uses to generate random numbers. Variables included to explain the analogy of the roulette wheel are velocity of the ball, and initial position of the ball.

DNA Walk- This program is one of many that explain how a random walk is translated into a natural phenomenon. Here a random walker generates a fractal landscape. The landscape created by the random walker is analyzed and compared to a similar "landscape" derived from the profile of amino acids found in the DNA of sample genes.

C.2 Fractal Dimension Unit

This unit introduces the measurement of an object's fractal dimension as a way of understanding similarities in the wide variety of structures that grow through random processes.

Hands-On Activities

Fractional Dimension- Students generate a "gasket" by folding pieces of paper and cutting out certain sections. When they have completed their "gasket" the students measure the dimension of their product by covering it with squares. Students graph the results of their measurements and uncover what exponent yields the straightest line plot. This exponent is the dimension of their "gasket".

Testing Log Plots- Students are introduced to logarithms as a tool to take the guesswork out of finding the dimension of an object. In the previous activity, Fractional Dimension, students had to plug in exponents until they got the straightest line. Use of a log-log plot yields the dimension directly from the slope, eliminating number plugging.

Coastline- Students measure a given coast by "stepping it off" with calipers set to different lengths or by "covering" the coastline with different sized grids. Does a caliper set to five miles take twice as many steps along the coast as a caliper set to ten miles? No. Why not? It has something to do with the *dimension* of the coastline. Students collect data for various step sizes then plot their results on a log-log graph, finding from the slope the dimension of their coastline.

Laboratory Experiments

Bacterial Colony Morphologies- Bacteria are set in a flat bottomed dish with a thin layer of gel (agar) containing a nutrient. As the bacteria reproduce and spread across the agar they create a fractal pattern. (See Figure 3). This pattern can be analyzed by tracing it onto a piece of paper and measuring it or by scanning it into the computer and using the *Fractal Dimension* program.

Termites — Termites forage for food in sand between two plates of plexiglass spaced by 1/32". The termites enter the cell through a hole in the center and then dig tunnels in search of food. Students can study the pattern by image grabbing with a video camera, or by scanning the pattern, and then using the *Fractal Dimension* program.

Computer Programs

Fractal Coastline- Coastlines are randomly generated based on conditions set by the student. Student measures the fractal dimension of the resulting coastline using the computer version of the methods employed in the hands-on activity: "walking" with rulers of different lengths or "covering" with grids of various sizes. The computer records the data and allows students to create graphs based on their data to find the dimension of their object.

Fractal Dimension- This program gives the student a variety of objects to measure to determine their dimension. The program offers two measuring methods: (1) the box method which covers the object with different sized boxes and records the number of boxes it takes to cover the object; and (2) the circle method which covers the object with concentric circles and records how much of the object is within each circle. The program graphs the results of its measurements and allows the student to choose which data points they want the computer to graph. Objects from the "real world" (including patterns grown in laboratory experiments) can be scanned into the computer and imported into this program for analysis.

C.3 Aggregation Unit

Students apply their knowledge of a random walk, introduced in an earlier unit, to a particular natural phenomenon: the growth process of aggregation. The idea of fractal dimension is integrated as one way to measure the pattern, or aggregate, produced from the process.

Hands-On Activities

Pattern Building- Students model the movement of an ion in solution by charting the results of a two dimensional random walk. An ion starts on the outer edge of a circle and takes steps to complete a random walk. The direction of the steps can be determined by rolling a tetrahedral die or by following entries in a randomly generated table. If the ion reaches a structure previously grown from the center, it sticks to it; if the ion exits the circle before touching the center it is removed and replaced by a new random walker. After many walkers stick to the growing structure, they form a fractal pattern or "aggregate".

Laboratory Experiments

Electrochemical Deposition: Students grow an aggregate by passing an electric current through a solution (either copper or zinc sulfate) held between parallel plates of Plexiglas. (See Figure 3). The resulting aggregate pattern depends on student-controlled variables including molarity of the solution, size of the anode ring and the applied voltage. The resulting laboratory pattern is scanned into the computer and its fractal dimension analyzed using the *Fractal Dimension* program.

Hele-Shaw: This experiments demonstrates the phenomenon of viscous fingering. Students inject air (which is the less viscous fluid) into glycerin colored with food coloring (which is the more viscous fluid). A fractal pattern results along the boundary between the air and glycerin. The process is quite fast, and can be captured using video imaging software. An image of the created fractal pattern is analyzed using the *Fractal Dimension* program.

Roots: Seeds are planted in soil held in a Plexiglas container. Sides of the container are covered to keep light out and the soil is watered regularly. The seeds sprout and the paths taken by the roots in the soil are examined by uncovering the sides of the container. Typically this pattern is fractal.

Greased Lighting: A circular drop of lithium grease is placed on a piece Plexiglas. A second piece of Plexiglas is pressed on top of the first and firmly held for a few seconds. The top plate is slowly removed. As the plates are separated, air enters the grease and forms a fractal pattern. (See Figure 3). This pattern's fractal dimension is determined by scanning the image into the computer program *Fractal Dimension.*

Crystallization: Evaporation cooled solutions of ammonium chloride become supersaturated. If the solution is gently heated, dendrites of ammonium chloride precipitate. These are clearly visible under the microscope. Different dendritic patterns emerge, depending on the drying rate. With a video microscope students can watch this dramatic crystallization, and grab images. A similar experiment can be done with super cooled ammonium chloride solution. When agitated, snowflakes of ammonium chloride precipitate. If copper sulfate is added as an impurity, the symmetry of the snowflakes changes.

Cracks/Erosion: Drying of potato starch on filter paper results in a pattern of cracks reminiscent of a dried river bed. The patterns formed may be scanned into the computer and analyzed using the program *Fractal Dimension.*

Dielectric Breakdown Patterns: When electrical charges are separated, either in air or in a solid dielectric medium, an electric discharge can result. The breakdown pattern is manifested as lightning in air, one of the most spectacular of all natural phenomena. This pattern can be reproduced on a small scale, either as a volume phenomenon, by injecting electrons in plastics, or as a surface discharge phenomenon on a resistive medium. Analysis of the resulting patterns leads to its fractal dimension. Computer simulations can then be compared with the laboratory generated patterns.

Computer Programs

Fractal Dimension: Within the Aggregation unit, students employ the more sophisticated parts of this program which was introduced earlier. As part of this unit computer and laboratory generated aggregates are transported into the program to determine their fractal dimension. Students can compare the fractal dimension the computer arrives at to the measurement they derive mathematically.

Aggregation Kit: This program automates the student hands-on activity of pattern building. The student can generate computer aggregates by setting a number of variables. The program allows the student to split screens an observe two aggregates at once in order to determine the effect that changing variables has on the aggregate that grows. Aggregates generated by this program can be saved and transferred into the *Fractal Dimension* program to be analyzed.

Chill Out: This program enables the student to create and analyze a simulated aggregate, or choose to analyze an aggregate from the computer's files. The student can determine the effect energy has on the formation of the aggregate by experimenting with the program's options. For example, the *force lines* option draws force lines on the screen and allows the student to launch a single particle which will join the aggregate. The path the particle takes can be compared to the predicted lines of the force.

Spiral Galaxy Structure: One of the largest regular patterns seen in nature is exhibited by spiral galaxies. The origin and persistence of these patterns, despite the presence of differential rotation in galaxies, can be shown to arise from a simple set of probabilistic rules related to the "game of life," a percolation phenomenon simulated on a Macintosh computer. Various types of spiral galaxies result from different student choice of parameters. These can then be compared to photographic images of real spiral galaxies.

C.4 Disordered Systems Unit

The study of fractal patterns is the study of how order comes from disorder. This area of study includes not only examinations of pattern growth in nature, but also investigation of mathematically generated, self-similar patterns. In this unit students are introduced to such patterns and the idea of self-similarity on an infinite scale.

Hands-On Activities

The Chaos Game: Students begin by placing three dots on a piece of paper and numbering them 1, 2, and 3. They also place a fourth dot, anywhere they choose inside the triangle drawn through the three numbered dots. Now they choose a numbered tile from a bag. They place a dot halfway between the fourth dot and the dot corresponding to the number they chose. They return the tile to the bag, shake, and choose again. This process is repeated a number of times. The class discusses what would result if they continued this process. Will the triangle be completely filled with dots?

Laboratory Experiments

Resistor Network: 1K ohm resistors are set up on pieces of circuit board in the shape of a Sierpinski gasket. Students measure the vertex to vertex resistance of the resistors in a gasket shaped, network of nine. The second generation is constructed by wiring together three first generation gaskets, and the resistance is measured again. This process goes on for a number of generations. The measured resistance is then compared to the student calculated, theoretical resistance of the network.

Computer Programs

GasketMeister: This program automates The Chaos Game. The student places the original three points and the computer rapidly carries out the process of adding new dots. What results from the process is not a solid triangle, but a triangle with empty spaces called a Sierpinski Gasket. The Sierpinski Gasket is a deterministic fractal that has infinite self-similarity. The student can experiment by placing starting dots in different geometric configurations, and setting the distance a new dot is placed from the starting dot, to see if a Gasket always results.

The Iterator: This program demonstrates how a line or shape when iterated to fit a curve, can be transformed into a self-similar object; or deterministic fractal. The program allows the student to experiment with the number of iterations completed using a pre-set curve (the Von Koch, Quadratic Von Koch, Gosper or Peano curves are available). The students may also choose to create their own curve.

C.5 Rough Surfaces Unit

This unit introduces students to the idea of analyzing the roughness of an object's surface in order to find the roughness exponent. The roughness exponent then becomes a numerical way to compare a variety of structures that represent different phenomenon, but look the same to the human eye.

Research on fractal patterns in nature has wider applications than simply understanding that order can grow from chaos. The rough surfacts unit can also explain how the application of concepts related to fractal forms aides scientists' understanding of polymers.

Hands-On Activities

2-D Random Walk: Students are given a numbered grid and a walker. The student begins by placing the walker in the center of the grid. The direction the walker moves (north, south, east, or west) is controlled by the roll of a tetrahedral die.

Paper Tearing: Students wrap a piece of paper around two sticks. One stick is held firmly in place while the other stick is pulled. The tension created from this action tears the paper. The tear is not, however, a straight line. The path the tear has taken across the paper is similar to the path chosen by the program *Directed Polymer* because it is the path that required the least amount of energy. The "landscape" of the tear in the paper can be scanned into the computer, analyzed, and the roughness exponent can be determined by using the *Surface Analyzer.*

Laboratory Experiments

Paper Wetting: A paper towel is dipped into ink and the ink is soaked into the paper. The surface created by the ink is can be scanned into the computer program *Surface Analyzer* for analysis.

Image Analysis: Student laboratory experiments (i.e., *Hele-Shaw, Lichtenberg*) and real images taken from nature (i.e., leaf patterns, photographs of lightning) can be scanned into the computer or digitized through the use of a video camera and frame grabber. The programs are rich enough that they can also be used to create images from the numerical data of digital elevation maps developed by the National Geological Survey (i.e., river patterns, canyon shapes, mountain ranges, and coastlines) as well as from satellite data collected by NASA's Magellan Mission of the surfaces of Venus. The *Fractal Coastline* program allows the user to produce a rough surface with controlled parameters and provides the student with options for analysis.

Computer Programs

Surface Analyzer: This program gives students a variety of options for analyzing the roughness that is found in the world around us. A number of stored images allows students to discover the roughness exponent of such things as the "landscape" of a section of human DNA. Students may also choose to scan into the program images created from laboratory experiments of objects they find in the "real world".

C.6 Fractal Noise Unit

Not all fractals can be seen. The abstract idea of fractals that exist not only in space, but in time as well, is introduced in this unit through the medium of music. The unit on Fractal Noise needs further development;both hands-on activities and experiments need to be created.

Computer Program

Fractal Music: This program demonstrates the rhythmic and melodic patterns of fractal noise, brown noise, and white noise. The computer generates music conforming to the conditions set forth by the student. Variables the student controls are, rhythm, pitch, tempo, and length of the melody.

D. Experiments to Accompany OGAF Units

D.1 The Role of Experiments in OGAF

A goal for the development of every OGAF unit has been the creation of hands-on activities and experiments to precede the use of computer simulations in a two-cycle approach to scientific modeling. Coached to think like scientists, students perform hands-on experiments not to confirm a priori concepts but to carry out systematic tests, collect and record experimental data, conjecture and make predictions, and compare their results to computer simulations of the phenomena they observe. When agreement is less than perfect, students are asked to speculate: Is this model a good fit to the experimental data? What important aspects of the experiment have been neglected in the model? How should the model be changed to represent the observed phenomena more accurately? Through this two-fold process of experimentation and modeling with computer simulations, the student learns that current science is not just laboratory verification of a priori concepts. Instead, the student have direct involvement in the central creative task of modern science: the imaginative construction and testing of new models to explain experimental observations. By exposure to scientific models--the artificial worlds that exist in the scientist's imagination, the precursors of full-blown theories--students come to understand that the scientist is much more a detective than a technician. They realize that it's okay to be wrong sometimes, and they learn more from "mistakes" than from retesting old theories.

D.2 The Experimentalist and His Team

An experimental physicist in mid career was hired to design experiments that could be conducted by high school students prior to using the computer simulations. Most of the initial experiments he presented and adapted for use in OGAF were ones he had been working on at the University of Michigan on which he had written several scientific papers. First were electrochemical deposition (ECD), the Hele Shaw experiment and several variants on this experiment, and then new experiments. The latter explored the growth of termite colonies, root growth, and bacterial growth using experiments which could be performed under high school conditions. Finally there were the Liesegang experiment, named after the scientist who first observed the patterns, dielectric breakdown, resistor networks, paper wetting, and paper tearing. The experimentalist noted that while the research represented cutting edge science on pattern formation, the experimental technology was relatively simple, and he was able to adapt them for use by high school students. This was an important consideration.

He noted that pattern formation is a field that had been too difficult to investigate mathematically prior to the use of computers, so a lot of the patterns we see in everyday life which were generated very simply were not actively investigated because there was no theoretical way of understanding them. Once computers became available which allowed the computations for analysis of these patterns, the challenge was to generate these patterns under controlled circumstances and then test them against computer models and against new theories that were being developed. Many of the experiments conducted at the University of Michigan were done by undergraduates under his supervision as they pursued honors theses.

At Boston University, a number of undergraduate students employed on work-study funds worked with the experimental physicist in his lab. They were attracted to the project both because they needed to earn money and because they wanted research experience. While the employment was "education driven" (requiring the development of experiments for use by high school students), the physicist pointed out that there was a research component to what they were doing. The undergraduate students learned how to do basic lab work. The scientist noted that some of the students proved to be essential to the project, while others turned out to be unreliable. "Very few completely evaporate. What simply happens is they use up their work-study money. The question really is, from my perspective, how many of them are really worthwhile workers? I would say maybe two in five." But he quickly modified this harsh criticism:

> "Having said this, when you go to the schools, you have to have some materials for the students to work with. Our undergraduates have done a great job in producing those materials. There has always been some shining star, someone who has really shined in getting the stuff out so that we could use it in the high schools. That's clearly the production side. On the experiment side, the basic ideas pretty much existed from day one and I'm not going to take any great credit for them. There are numerous articles about how to do ECD. There are also numerous popular lay science articles about how to do Hele Shaw. *Scientific American* has been full of those kinds of articles. We can't claim any great originality there, independent development yes, but no great originality."

The experimentalist was careful to point out that a "big breakthrough" came with the development of the fractal dimension program by one of the undergraduate programmers. Clearly fractal images were produced by the experiments but suddenly students could couple the experimental activity directly to a quantitative computer activity and analyze those images. This allowed students to compare experimental and computer generated images in a much more precise way. The fractal dimension program included the option to transport into program patterns which were scanned from images grown in laboratory experiments, and compute their fractal dimension. It was that coupling which we think excited the teachers about the possibilities to delve further into experiments. In particular, with electrochemical deposition, students could examine difference in the aggregate appears which resulted with changes in the solution (either copper or zinc sulfate), the molarity of solution, the applied voltage, the size or the shape of the anode. A wealth of possibilities existed whose fractal dimension could be studied mathematically.

D.3 Links to Computer Programs

Asked if the experiments inspired the development of computer programs or if computer programs drove the creation of experiments, the experimentalist replied: "Yes on both counts." He noted that there has been give and take. For example, the aggregation kit happens to be an example of a computer program algorithm which can be applied to many different physical phenomena. The result has been that we have used the aggregation kit as a way of modeling electrochemical deposition and as a way of modeling bacterial growth. In addition, he saw opportunities under a new NSF grant for Instructional Materials Development for a programmer to develop and complete programs which already exist. He also offered cautionary advice about the use of the *Aggregation Kit* program:

> "There is a pitfall in that the aggregation kit produces patterns which can lead the unwary user to think that they have solved a problem because of the visual similarity when in fact they may have missed the point. That it is not a trivial error because there was a span of time in the 1980s when a lot of papers were published with a lot of algorithms very similar to the algorithms in the aggregation kit reporting to explain physical phenomena when in fact the physical phenomena were different, and although there were some visual similarity, the two were not directly connected.
>
> That's exactly the reason the *Aggregation Kit* is so powerful, but on the other hand, it's important to teach them the other mark. With the help of another senior scientist, we've had a very nice development, especially recently, of the *Aggregation Kit* but that has been after many discussions about what should go into it. Similarly, the program *Deer* can be linked to Liesegang like phenomena however, we don't really have an experiment which is a micro ecology experiment appropriate for something like *Deer* , although I thought about how one might do that with bacteria. We don't have something like that at this point. I don't think anyone does.

The experimentalist noted in particular "definite limitations in the programs that we have seen in use with teachers and high school students, such as the ability to print graphs in some cases, or save the data, and these are issues that hopefully will be addressed and these are things that are brought to our attention by users of the program in the high school and by teachers." He offered the judgment that: "To the best of my knowledge all of the programs that we have now do what they report to do so the program does not have a technical programming bug in it."

D.4 Challenges and Limitations

The experimentalist inquired of himself: "The next question is does the program explain the experiment?" The programs are essentially generic, and while there are parameters that can be varied, they are not open, flexible programs in the sense of something like interactive physics where one can literally build the physical situation. Our programs are not programming languages or logo environments where one can build up a new algorithm and try to understand the physical phenomenon from a new algorithm.

"Instead, our programs are algorithms which have been developed in the past and our students can manipulate and use the existing algorithms the way that a researcher might use the existing ones to explain the phenomena which the program was written to explain with all the limitations also for which the program was written. That does not mean however that the program was written to explain, for example, electrodeposition. The aggregation kit does not explain electrodeposition. We know that very clearly. That's known in the research literature.

There was a time when papers were published which essentially use the algorithm which is the basis of the aggregation kit to explain ECD though such a paper could not be published again because science has developed, research has gone on, and we have discovered so many new things. So, if you were to ask me, is the aggregation kit wrong when it is applied to ECD I would say, well the aggregation kit isn't wrong, however, if you are blindly explaining ECD using the aggregation kit, that is the wrong program to use to explain the ECD experiment. That doesn't mean that the model doesn't give you insight into the experiment."

There are many things which the algorithm for the aggregation kit embodies which you see in the ECD experiment. That includes branching phenomenon, the rate of branching in some cases, and screening effects. All of these things absolutely do occur in the experiment. All of these are properties of the aggregation kit. That doesn't mean that the aggregation kit explains ECD because I can list a dozen things which the aggregation kit does explain about ECD. That's why the question that in fact you suggested we be asking in the classes in Weston as to what the limits are where the program agrees and where the program disagrees with the experiment is a critical question which should be asked of any user

D.5 The Role of the Teachers in the Development and Use of OGAF Experiments

The evaluator noted: "Clearly in my visits to the schools, the students' receptivity to some of the experiments that you have provided to them has been overwhelmingly positive. To what do you attribute this success? Is it the people here at the University? Your own original ideas? Collaboration with teachers? Interaction with students?" The experimental physicist credited all of these sources, but gave special recognition to the teachers who collaborated with him in suggesting what could be done with experiments, and how existing experiments might be adapted for use in the high schools to promote student interest and engagement.

The opportunity for students to do quantitative analysis of the patterns they generated was a critical break through. The physics teacher liked the Grease Lightning experiment which is a variant of the Hele Shaw experiment on viscous fingering; the students put grease between two plates, peal them apart, and do a quantitative analysis of the resulting patterns after scanning them into the computer. Another variation which they do uses paint between plates which they can later use as key rings.

The teachers have been essential in the way that they have gone about using the ECD experiment, which went beyond being just a demonstration. "Otherwise every experiment we do is just another demo of pattern formation. There are hundreds of such demos, but there is no way to analyze them. So the way they were willing to take the standards into their classrooms and use them in conjunction with the experiment really made it. One teacher was also very creative with respect to the Hele Shaw experiment. We are still having some difficulty with that experiment even after four years or five years of doing it. One of the problems was that initially we did the experiment with the injection of air into glycerin and despite the fact that I had done water into glycerin for research purposes, it didn't really occur to me until last year that we should try the water experiment instead. The air into glycerin experiment unfortunately leaves a ethereal pattern that just vanishes very quickly as opposed to the water into glycerin which retains the pattern and then the student can grab that image for data analysis.

D.6 Plans for Use of the Experiments in Other Science Disciplines

Asked "What would you do differently? Are you suggesting that perhaps we need a greater diversity in the disciplinary backgrounds of the teachers?", the experimentalist replied: "Yes, I've been pushing for quite a while to hire a biology teacher but unfortunately there was apparently no additional money. No one has analyzed the termite pattern in the classroom as yet. It's not that they can't, but we haven't had a biology teacher. We've had no teacher to try out the *Roots* experiment, we've had no teacher to try out the *Bacterial Growth* experiment. And there's also the matter of time. (A biology teacher) at Weston expressed a great deal of interest in working with our biology materials. She is very interested but I have not had a chance to follow up with her as much as I would like to have. On top of that, we had bad luck this past year. A few times she planned on using the experiment and it was another snow day and in the end there was so much snow. She was all set to do the bacterial growth experiment and we lost it."

The experimentalist hopes to reclaim some of these opportunities with the two grants that are coming on-line--for Teacher Preparation and Enhancement and for Instructional Materials Development.

"I'm expecting alot of the current teachers; there is one teacher from New York State who said termites fits in best with her particular curriculum constraints of the New York State Regents. Other teachers developed experiments that I would not have thought of such as doing leaf rubbings and then doing computer analysis of leaf rubbings. I'm very anxious to get that into our IMD curriculum and into our TPE resource book. So I think that there are lots of things that could happen in the future with respect to biology. We also have to go into the earth sciences a little bit more in the future. Unfortunately earth sciences are very slow, geology is the slowest, so the problem is to find the appropriate experiments to match geological formations.

E. Strategies for Program Monitoring and Evaluation

A variety of strategies were used to gauge the effectiveness of the OGAF Project on an ongoing and timely basis and to monitor its development and implementation as well, including: (1) consultation with experts in science and education; (2) case studies and clinical trials with pairs or small groups of students at the Boston University Center for Polymer Studies; (3) field trials in area high school classrooms; and (4) continuing documentation of the process of development and implementation. Specific strategies in each of these categories are outlined below.

E.1 Professional Consultations

- Resident scientists (professors, post docs, and Ph.D. candidates)
- Resident educators (professors, post docs, and Ed.D. candidates)
- Master teachers in the field
- Visiting international scientists
- Members of the OGAF project's advisory board

E.2 Case Studies/Clinical Trials at BU Polymer Center

- Pairs of students

- Intake interview
- Unstructured observation
- Videotaping
- Think aloud interviews
- Probing questions
- Keystroke monitoring
- Low inference, structured observation; activity tally
- Repeated trials over time
- Exit interviews
- Long-term follow-up interviews

E.3 Field Trials In High School Classrooms

- Intake interview
- Preconceptions and misconceptions questionnaire
- Ethnographic field notes
- Multiple observers
- Videotaping
- Focused observation of selected students
- Classroom handouts
- Examples of students' homework and reports
- Electronic journals or learning logs which students kept on computer
- Teacher logs
- Teacher debriefings
- Meetings with Superintendents
- Informal exchanges with S's
- Follow-up questionnaires
- Exit interviews

E.4 Documentation of the Development Process

- Unobtrusive measures
- Minutes of staff meetings
- Unstructured observations
- Interviews with professional staff
- Interviews with graduate students

- Interviews with undergraduate programmers
- Changes in programs over time
- Field notes on social dynamics
- Changes in management plan felt by participants
- Changes which appear in reports and proposals to NSF

F. Findings from Initial Formative Evaluation

Before any of the OGAF units were tried in classrooms, they underwent three kinds of screening to review their scientific accuracy, to gauge their appeal to high school students, and to determine if the programs were robust enough that they would not crash. These filters took the form of professional consultancies, clinical trials with small groups of students at the Boston University Polymer Center, and extended case studies with various pairs of students, also at the Polymer Center.

F.1 Feedback from Scientists and Teachers

A large number of programs were attempted, but "only about 15% of the initial ideas were finally incorporated into the main body of the OGAF collection" according to senior scientist who oversaw the work of the undergraduate programmers. Asked if there was a formal set of criteria for deciding to go ahead with a program or to stop further development, he replied that he consulted with three to eight people to make that decision. The co-PI was always consulted, along with the Project Manager. The high school teachers were also consulted on a regular basis. Once they encouraged continued development of a program, the *Deer* program, which the senior scientists did not think would be that useful. The teachers, on the other hand, saw applications in biology and environmental science which the physicists did not anticipate. In addition the educational researchers provided insights for the development and/or modification of programs.

The evaluator tried to elicit from the professional staff the criteria or considerations they used in judging a program to be successful or worthy of continued development versus termination. The scientist overseeing the undergraduate programmers named the following considerations: the program should employ animation techniques; it should have a colorful interface; it should be able to save data; and it should be usable in several modes. He named the *Aggregation Kit* program and *Fractal Coastline* program as the most successful of the OGAF collection of programs in meeting these criteria. Recalling a proverb from his homeland he noted: "In Russia we say 'If the theory is correct then you can explain it to a child of age 10. And it is not correct, you can't explain it to a child. The child will not understand....' That is why I think it is easy to explain the scientific principles to the undergraduate programmers." He thought it was harder to teach them programming because "this is unfortunately a very technical and sometimes a very boring discipline."

F.2 Results from Clinical Trials

During the first two years of funding, initial trials of OGAF materials and programs were arranged with small groups of high school students who traveled with their teachers to Boston University. These sessions provided opportunities to monitor student reactions to selected programs, to inquire of the high school students in informal conversations what interested them and what they had learned, and to note what content background, orientation, hands-on experience, and technical assistance were needed for students to use the programs effectively and with sustained interest. When successive programs reached the level of development to warrant student trials, new groups of high school students were brought to the Polymer Center to test their reactions.

These trials were oftentimes telling of student interest and understanding, with feedback both positive and negative. And when students did not reveal in words or behaviors what they really thought, their teachers got back to us with their true thoughts. 'When we came away from that session with the kids, they were quite honest with us: they simply said, "those people tried to shove too much down our throats too fast. Why were we there? What were we doing? It was nice day off, but 're not quite sure where it all was coming from."

F.3 Results from Case Studies of Minority High School Students

Another strategy initiated by the evaluator was the identification and recruitment of same sex pairs of minority students who came to the Boston University Polymer Center to advise us about the OGAF materials and programs; what did they learn; what did they like; what didn't they like; how can we make the programs more interesting, more engaging, more effective? The students and their parents consented to the students' participation in the case studies.

Two ninth grade Hispanic female students (given the pseudonyms Marie and Denise in this report) from the Boston Public Schools agreed to pilot-test the *OGAF* simulations. During separate initial intake interviews, each girl reported that she was enrolled in two freshman level science courses (physical science and biology for one of the girls, physical science and earth science for the other), but described science as one of her "least favorite subjects." Mathematics, particularly algebra, was described by both girls as "their worst subject in school." Two eleventh grade, Afro-American male students (called Larry and William in this report) from the Boston Public Schools also agreed to pilot test software. During the initial intake interviews, each boys reported that he was enrolled in general chemistry and geometry. Neither boy said that he particularly enjoyed science at school, although William did say that geometry was one of his favorite subjects.

Both the boys and the girls were promised a small stipend for participating in this research ($100 each for each six week period). On the first day, they were told that regular weekly attendance was required and that they would be paid after six weeks provided that they had not missed any of the sessions, although a session could be rescheduled for illness, holidays, snow days, or other unforeseen circumstances. The two girls came regularly to the Polymer Center and pilot-tested software for two full hours every Monday afternoon for twelve consecutive weeks. The boys' participation was much more sporadic. Often the boys failed to show up without contacting the research staff in advance or arranging to make up the session. In total, the pair of boys came to the Polymer Center four times over an eight week period. Two of the four times, the boys asked to leave one hour early so they could do homework or study for exams. When basketball season started, they discontinued their visits altogether.

Each afternoon began with a twenty-minute videotaped session in which the student pairs were interviewed. These interviews focused on identifying student preconceptions, soliciting student reactions concerning the previous week's activity, and/or discussing ways to improve the *OGAF* materials. Occasionally students would volunteer information and opinions about their science classes at school.

Then, students were videotaped as they worked together on each simulation. A very sensitive microphone picked up their comments to one another. They were encouraged to work through different part of the simulations and "think aloud." Undergraduate student programmers were available to answer questions or assist students when necessary. More than thirty hours of videotaped interviews and observations were collected from these four students. At the end of the twelve weeks, the two girls were interviewed individually. These exit interviews were also videotaped.

In addition to testing students' reactions to the programs, the case studies provided an opportunity to uncover the students' preconceptions concerning randomness. William correctly recognized that randomness means "you don't know what is going to happen next." "[Randomness is] if you don't know what's going to happen right off the bat, but if you know what's going to happen, then it's not random." William did not think that events with 50% probabilities were random. Coin flipping was not random to William because he felt his chances of predicting the outcome was relatively high. His ability to predict where lightning will strike a pasture was relatively low, so he believed this event was random. William appeared to hold the preconception that randomness is a measure of one's ability to predict an event. Recognizing that coin flipping is random is considered prerequisite for many OGAF activities. Hands-on activities and simulations use coin flipping to generate fractals in the hopes that students will discover that order is often created out of randomness. This important point will be lost unless students abandon the belief that coin flipping is not random.

These kinds of intensive and extensive observations gave us the unique opportunity to examine the effects that visual, highly interactive simulations have on the conceptions and attitudes of minority female students. The girls became excited about fractal geometry and learned quickly to identify fractals in nature. For example, although she described geometry as one of her worst subjects, Marie regularly cited various examples of fractals she had observed during the week (including parsley -- an example we had not introduced to her). On several occasions, students volunteered that their experience at the Polymer Center was more beneficial than their high school science classes. Marie was most emphatic on this point. Here, she describes why she is learning more science at Boston University than she is at school:

When you're at school and [the teacher] is just up there telling you stuff, you don't really know what they're talking about. Let's say you have two views. One is actually knowing it yourself, the other is having someone tell it to you. You could really look at the stuff yourself [and] understand it better than [if} the teacher [is] up there [saying]: "It's like this and like this." Cause [the teacher] says its like that and you say "okay -- it's like that," but you don't really understand it unless you see it yourself.

F.4 Results from Early Classroom Trials

As computer equipment became available through equipment grants to the project, graduate students and senior staff traveled to the schools during the Spring term of the 1990-1991 academic year, transporting and setting up the equipment for use in "real live classrooms." Of course, these situations were artificial in that the experiments, demonstrations, and accompanying programs were pried into the curriculum for a day or two in each school. Nonetheless, these initial experiences in three schools offered valuable insights into what it takes to make our materials feasible and worthwhile in the schools. We made many important observations:

- newly manufactured equipment for the hands-on experiments might need adjustment;
- equipment thought to be routinely available in high school science laboratories may not be so routinely available;
- students can become so fascinated by the results of electrochemical deposition experiments that they don't want to destroy their results to continue the experiment with a new material;
- students enjoy seeing each other's results and their verbal comments describing what they and their classmates have produced yield a vocabulary for description and discussion of the different outcomes with different solutions;
- what science is needed to engage in explanation of the results became an issue;
- connections between the experimental results and the computer simulations were interesting to most students;
- the visualization of phenomena was a great assist to conceptualizing the phenomena and to comparing differences in patterns due to setting different conditions (molarities, current, and solutions);

- teachers and students needed much more time to discuss the results and consider various explanations, both from the workbench and the computer;
- both the BU people and the classroom teachers were too directive in their initial early trials in the schools, perhaps due to the compressed (in time) usage of the materials in the schools;
- effective teaching with OGAF materials will require new roles for teachers in the classroom if students are to engage in real inquiry.

Other physical experiments addressing the same concepts were introduced (Hele Shaw and surface tension experiments) but with too limited time for discussion. Connections with computer simulations were made by several students but were underdeveloped for all, due primarily to lack of time. The location and pacing of the new modules in the curriculum became issues of intense interest for members of the university team and the high school teachers. The high school students surely could have informed our concerns, but they had to rush off to their next classes.

Ph.D. candidates and undergraduate programmers have been participants both in these small group "clinical" trials and the field trials, as well as the debriefings offered by the senior staff on what was learned. In response to these observations, and in criticism of their own efforts, the programmers have been working to standardize interfaces within languages and machines, create more opportunities for student controlled interaction in the programs, create opportunities for students to save their results and to compare patterns gained from different trials, setting different conditions and parameters, using flexible. Two of the most gifted programmers who were working on the project reported in separate interviews how exciting it was for them to see students using their programs in high school classrooms and how much they learned from the experience.

G. Field Trials in Area High Schools

G.1 Choice of Field Sites

At the outset of the grant award, physics and chemistry teachers in three suburban school systems were contacted by the evaluator. She described the project, outlined its goals, and inquired about their interest and availability to participate in the OGAF. Their disciplines were chosen because they matched the early plans for development of materials and programs, as well as the disciplinary roots of the senior project staff. Our extensive informal educational network, particularly in science education, pointed to these individuals as highly competent teachers with a solid grounding in their science. While we deliberately sought inner city minority students for clinical trials and case studies to be conducted at Boston University, the senior staff agreed that we needed talented teachers to work with us in developing and field testing the materials--teachers who would not be easily intimidated working with university scientists, who were very knowledgeable about their subject matter.

We did not presume that we would not be able to find outstanding science teachers in inner city schools, however we also argued that we needed teachers who worked in school systems where innovation would be allowed even in structured courses following syllabi driven by standardized examinations and where very expensive computer equipment could be secured. While some of these criteria arguably might be met in urban schools in the greater Boston area, we opted to pursue initial field trials in suburban schools which held greater promise for getting beyond administrative and logistical problems to opportunities to examine use of our materials in the classroom.

A physics teacher from Belmont High School who was a Presidential award winner, and a chemistry teacher from Newton South High School were invited to participate. At the third site, Weston High School, the evaluator requested the participation of a chemistry teacher and a physics teacher, both of whom had been cited for their excellence in teaching, so that cross disciplinary opportunities might be explored. The chemistry teacher who was also the science department chairman, reported that the physics teacher would not be able to participate due to a family tragedy. Instead, he recommended that we invite his colleague who was the new chairman of the mathematics department and very knowledgeable about computers in education. We did so, and the mathematics teacher accepted.

G.2 Differing Patterns of Involvement: Independent; Collaborative; or Top Down

All three schools were located in highly advantaged suburban communities. It was not so much differences among the high schools, as the initiatives, courses, and personal styles of the teachers that seemed to influence the different patterns of involvement at each site which took hold over the life of the project. The physics teacher in Belmont worked independently. He was responsible for teaching several sections of the regular introductory physics course and he taught an advanced physics course as well. In the introductory courses he felt obliged to stay close to the traditional physics curriculum which would be tested on the SAT physics achievement examination (now one of the SAT II subjects tests). High stakes testing was not a factor for the advanced course, so he felt free to alter it as he saw fit. Some of the OGAF materials became a focal point for one of the four units he taught in this course. He concentrated his efforts on OGAF with 15 to 20 students, committing up to eight weeks of his course to OGAF. He collaborated extensively with the OGAF professional staff at Boston University and with the three master teachers from other schools. Additionally, he supervised two student teachers in the use of the OGAF materials, but he did not collaborate on OGAF with regular teachers in his own school.

In his first year of involvement in the OGAF project, the chemistry teacher at Newton South appeared to fit OGAF materials into his existing courses as an add-on. He too felt constrained by the influence which the SAT achievement examination exerted on the content of the course. He did not invite collaboration of colleagues in the use of OGAF materials at this point. However, once he became more familiar with the materials, and the materials themselves were improved, he offered three workshops for his colleagues. Later, when Newton South was chosen to be the site for extensive field trials of the WAMNET materials (another project in Applications of Advanced Technology which was based at the BU Polymer Center), he needed to secure permission and cooperation of many people in the school, including administrators, faculty colleagues and even the custodial staff.

In Weston, there were elements of both collaborative and top-down approaches to promote involvement in the use of OGAF. Because the two teachers who were chairpersons of two different departments sought to work on the project together, there was collaboration right from the start. In their eagerness to promote the use of OGAF materials in several different classes, involving both honors and regular students, in chemistry, physical science, and mathematics classes, the two teachers committed portions of the curriculum in their own classes to OGAF and they arranged for two other teachers in their departments to share their classes as well. The latter arrangement meant that the department head requested a subordinate to yield her class to the master teachers, observe, and then model the continued use of OGAF units in their own classes.

In retrospect, the department heads realized that this was perceived as more top-down than collaborative, with less than satisfactory consequences. As well, the assistant superintendent for curriculum was concerned that the two department heads were spending too much time in planning and implementing the new OGAF curriculum at the expense of their other duties, most notably the evaluation of the teachers in their departments. Learning from these misunderstandings, the two department heads sought other ways to involve more teachers with the expressed support of the administration. These efforts took the form of professional development meetings, summer workshops, and grant-supported team building on weekends and in summer meetings, much of which focused on OGAF curriculum materials.

G.3 Technical and Logistical Requirements

The award of an equipment grant from Apple Computer Corporation meant that field testing of OGAF materials could begin in the schools. Until that point, teachers brought small groups of students to the Polymer Center, or the project staff brought computers to the schools on a short term. In either case the situation was contrived and rushed, and the feedback and observations were helpful for early stages of materials development but not useful for gauging real classroom response. The arrival of 12 Macintosh computers enabled us to begin field testing under conditions that were more typically found in schools.

After careful consideration and negotiation with the teachers, the project staff decided to place one computer with each teacher so that each one could become familiar with the units themselves and have the opportunity to use the unit in classes for small group or demonstration purposes. The remaining eight computers would be rotated among the three schools according to the schedule they planned for using OGAF. Belmont would have the computers in the fall from October through December. Weston would receive the computers in January and continue using them through mid March. Then Newton South would have them for the remainder of the school year. This schedule allowed maximum use of the computers while accommodating to the fullest extent possible how each of the teachers saw fit to incorporate OGAF into their course schedules.

Security for the computers was a critical issue. The Principal investigator wanted to be sure that the schools would take precautions against theft and vandalism, as well as environmental threats and accidents, including chemical pollutants and spilling water and other liquids. In Belmont, the computers were kept initially in a separate room down the hall from the physics teacher's classroom. The Newton South teacher was able to negotiate the use of a small office to house the computers across the hall from his classroom. In Weston, the science department chairman kept the computers in his own classroom, on lab benches to one side of the room (with no water use permitted) and on tables and desks at the rear. Hands-on activities were conducted on the movable desks in the middle of the classroom which could be joined to make larger work spaces. Wet labs like electrochemical deposition were conducted at the lab benches on the other side of the room across from the computers. The mathematics teacher taught in the science classroom when he team taught with the science chairman and even when he taught his own courses independently. Later in their rotation, the computers were moved to another classroom across the hall from his mathematics classroom.

The arrangement with the computers housed in the same classroom where teaching took place proved to be the most natural and beneficial placement. Students moved seamlessly between hands-on activities and experiments, and modeling the observed phenomena on the computer. In Belmont, the teacher worried that students in the computer room were not within his immediate control when he was in the physics classroom. He "felt frazzled trying to be in two places at once." Upon hearing from the project staff and educational researchers the benefits of placing the computers in the same classroom, he changed his initial arrangement to model the Weston situation, which proved to be much more to his liking. In fact, he noted that "if anything is the key to success of teaching these materials, it is having your students have instant access to the computers.... And, if someone said to me 'Well, aren't you concerned about someone spilling water in the keyboard?' It hasn't been an issue."

The Newton South teacher was similarly dissatisfied with the initial arrangement he had. The small office could accommodate only half his class at most. He thought it was artificial keeping half of his students in class and shifting the other half of his students to the computer, back and forth. He too worried about the lack of control. When Newton South was designated to receive RISC machines and be the site for field testing the WAMNET units, he was able to win support for the conversion of a much larger room, formerly used for storage, to house the new RISC machines and the Macintosh computers in their normal rotation on loan. The new room was adjacent to his chemistry classroom, with an inside door joining the two rooms, so the students did not have to exit into the corridor. He felt comfortable monitoring both rooms, especially as he and the students became more purposeful in their use of the OGAF materials.

H. Impact on Teaching and Learning

H.1 Fitting OGAF into the Curriculum

A deliberate decision was made by the OGAF development team at the outset of the project: we would not attempt to invent a new high school science curriculum; rather we would create units of instruction, based on new and important topics in science, which could be infused throughout the high school science curriculum and which could infiltrate mathematics education at the high school level as well. We sought especially to develop units which could have interdisciplinary applications.

The teachers we asked to examine the units were eager to consider where they might incorporate new topics and cutting edge science into their courses. Their response and actual use were a function of what they taught presently, what new topics they were willing to explore, whether they felt their students could handle the materials, and most especially whether their students would be taking SAT achievement examinations. The mathematics teacher in Weston was immediately receptive to the use of OGAF materials in his classes:

> I think it hit a responsive chord with me because it also had to do with fractals. I had done a little independent reading and had done some workshops on fractals from a mathematical point of view. And I really felt that that was a significant but underdeveloped area of the mathematics curriculum. The concept of chaotic behavior with non-integral dimensions was something that students of mathematics ought to be becoming aware of, since it could have a significant impact on the mathematics they would be studying and developing in the future. So since I was already teaching freshman Honors Geometry students, and rethinking what ought to be in a freshman geometry course, it struck me that there really ought to be a way of incorporating these kinds of shapes in a geometry course. So it hit that responsive chord with me. I could see connections between it and what I was teaching. I could see that it was current stuff that ought to be a part of the course. My excitement as a teacher is that what I teach is always changing and growing --things are dropping out, things are coining In to make it a living course curriculum, not a static subject matter.

As chairman of the department, he felt that he had a lot more flexibility. "There isn't anybody looking over my shoulder telling me that I am supposed to be teaching this material now." He first used the OGAF materials with his precalculus course, which he considered to have a "loose syllabus." "The required materials of trigonometry and polynomial arithmetic can be covered perhaps in a third of the year, which leaves me with two-thirds of the year to do any topic that interests me or that I think will be of interest to the students."

The other course he targeted for use of OGAF materials was the freshman geometry program. He noted that when he was approached about OGAF he had been reading James Gleick's *Chaos* . "It struck me that what he (Gleick) was saying was that we in mathematics were ignoring the important stuff. We were ignoring the examples that didn't fit the rule. We were writing those off as scientific error.... It struck me that Mandelbrot's comments about balls not being perfect spheres certainly applied to the study of geometry. Geometry is the study of shapes, and you really should be studying a variety of shapes, not only the traditional Euclidean shapes, so I felt justified in including them." But he also worried about taking time from the traditional standard fare. Essentially, the OGAF unit on fractals replaced 50% of the unit that he did on similarity.

Similarly, the physics teacher in Belmont was very receptive to using OGAF materials in his advanced physics class. When he was hired in Belmont, he was asked to teach an Advanced Placement course, but not enough students signed up. Instead he proposed to offer a second level physics course which would address contemporary topics in physics. He claimed two benefits for the new course: "one, these are things that the kids always want to find out about; and two, the topics are closer to current physics rather than physics that was done 200 years ago." The OGAF materials presented a good fit to the first unit in his advanced course. With continued improvement and refinement of the OGAF materials he committed more and more instructional time to OGAF, from a few class periods of demonstration in 1990-91 to four weeks in 1991-92, to six in 1992-93 and almost eight in 1993-94. However, he did not attempt to use OGAF in his traditional, introductory courses. Instead he stayed close to the curriculum which would be tested in the SAT physics achievement examination: optics, light, mechanics, electricity and magnetism "and a little bit of atomic and nuclear physics if you get to it."

The impact of high stakes testing could be seen in the choices the two chemistry teachers thought they could support. In Weston, students typically did not take the SAT achievement test in chemistry. Their sequence of course taking in science starts in freshman year with honors biology, followed by physics. And most of them take achievement tests in those two sciences. Having had two achievements, they no longer need a third, when they take chemistry in the junior year. The Weston chemistry teacher was less concerned with his students test performance and more willing to explore new topics and approaches. In Newton South, the sequence of physics and chemistry course taking is reversed. Chemistry students there do need to take the SAT achievement examination in chemistry, and the teacher felt obliged to follow the topics covered on the exam more closely.

Whenever the teachers saw in the OGAF units new and better ways of teaching topics which are already part of the "standard fare" they were especially enthusiastic about adopting the new material. As the chemistry teacher from Weston noted:

> I could neatly slip electrical deposition into the course.....Molecular chemistry is pretty standard fare: the whole notion of cells, electrochemical cells, electrolytic cells, oxidation-reduction. But it gave me a whole new way of bringing things into the classroom. Students do copper plating. It's one of the standard things you do with an electrolytic cell. But when you do it with the electrical deposition set-ups that (the eperimental physicist from Boston University) supplied to us, then it's a whole new ball game, and it's perceived very differently. You can bring in the notion of diffusion as a random walk, or at least a biased random walk, because it is an electrical field that is at work there.... I shared with my kids that this was cutting-edge stuff, that I didn't know the answers to some of the questions I was asking them because I'd never done it before, and they really got into it. They really enjoyed it. And the reports were excellent, as they were again this year.

He was not as comfortable moving OGAF materials into his ninth grade physical science class. Despite the fact that the curriculum was the most flexible of any of the science courses in his department, and there was no influence from high stakes testing, he was not sure that the students were academically ready for the concepts developed by OGAF. He also wondered whether they were mature enough to work independently with the computers. He and his colleague in mathematics tried to implement some of the OGAF materials with a group of students in the freshman physical science course whom they judged to be lower achieving. The students were very enthusiastic and surprised the teachers with their ability to master some concepts in probability and critical phenomena. But the teachers had attempted to work with five different classes at once, and did not give the extra attention to preparing for the use of OGAF materials with the lower achieving students.

H.2 Observations of Extended Classroom Field Trials

From the start, the plans for evaluation had been to pursue systematic inquiry starting with formative assessment and documentation of the teaching learning processes with OGAF materials. We started with early trials of the new hands-on experiments and computer-based simulations in small group laboratory settings, followed by informal field trials, and then more realistic field studies of classroom use of the revised materials through comprehensive observation and interviewing in high school classrooms.

Classroom field studies were used to accomplish the following objectives: (1) to formatively evaluate OGAF simulations, "hands-on" activities, and experiments, (2) to document the most effective combination of hands-on activities, experiments, and simulations, (3) to determine how to fit OGAF concepts into the high school curriculum, (4) to document the effects we observed with the use of OGAF materials, especially on female and minority students.

During the 1991-1992 academic year, mathematics and science students at Belmont and Weston high schools pilot-tested *OGAF* simulations, "hands-on" activities, and experiments. Table 2 describes the classes that participated in the field test and lists the simulations and experiments that were used. Over 120 students participated in the field testing. One of the Weston High School physical science classes was composed largely of minority students from Boston. These students were part of the Massachusetts METCO (Metropolitan Council for Educational Opportunity) program that gives disadvantaged urban students the opportunity to attend more advantaged schools in the suburbs.

A total of twelve Macintosh II and IIci computers were made available to the schools, one to each of the four teachers on a long-term basis and the remaining eight to the schools on a rotating basis. These computers were donated to Boston University as part of the Apple Classroom of Tomorrow (ACOT) program. We loaded

Table 2: Description of Classes Participating in Field Testing

Belmont High School

Name of Class	N	Software	Experiments
Physics II (12th)	24	Random Walk Anthill 2D Random Walk Forest* Blaze* Percolation* Fractal Dimension Fractal Coastline Chaos Game Aggregation Kit	Hele-Shaw Electrodeposition Resistor Network Crystal Growth

Weston High School:

Name of Class	N	Software	Experiments
Physical Science (9th)	27	Random Walk	
Physical Science (9th)**	16	Fractal Coastline Forest* Blaze* Iterator	
Honors Geometry (9th)	21	Fractal Coastline	
Honors Geometry (9th)	24	Forest* Blaze* Iterator Fractal Dimension Chaos Game	
Honors Chemistry (11th)	13	Fractal Coastline Forest* Blaze* Iterator Fractal Dimension Aggregation Kit Diffusion Chamber	Electrodeposition Diffusion Resistor Network
Honors Math 4 (11th)	16***	Iterator Fractal Dimension Forest	

Source: Erickson (1993)

* These simulations were developed by the WAMNet project.

** Ten out of 16 students in this physical science section were minority students from Boston enrolled in Weston High School as part of the METCO program.

*** Twelve of these 16 students were also enrolled in Honors Chemistry.

each computer with *OGAF* simulation software. One Mac II computer was loaned to the participating teachers in each school well in advance of field testing so that they could get familiar with the programs and decide which lessons they wanted to use with their students. *OGAF* developers also showed each teacher how to do the "hands-on" activities and experiments. We instructed teachers to incorporate whatever OGAF lessons they desired into their curriculum in any way they felt would be most beneficial to their students. The only advice *OGAF* developers gave teachers regarding classroom use concerned the appropriate pairing of "hands-on" activities and simulations, possible ways to sequence of *OGAF* units, and which simulations would best model the outcomes of the experiments.

The primary methods of data collection used in classroom field testing were extensive observation and interviews of students and teachers. Observers used a variation of a method of data collection described by Schofield (1991). As in Schofield's work, extensive handwritten notes were taken during each class period and then immediately transcribed. These notes included detailed descriptions of events, transcriptions of student-student and student-teacher conversations, and observer reactions. Observers were instructed to make clear distinctions between their reactions and their descriptions of real events. As in Schofield's work, to reduce the possibility of observer bias, two note-takers collected data in each class whenever possible. Their notes were compared on a regular basis so that biases could be identified.

In addition to field observations, we interviewed students and their teachers formally and informally. Students were interviewed both informally (while using the simulations and other materials) and formally. Formal interviews of students proceeded as follows: We interviewed a randomly selected sample of students immediately before and after the field tests. These interviews were structured and consisted of questions concerning student conceptions, attitudes toward science and science learning, and reactions to each of the simulations they used. We debriefed teachers informally after each class session and documented their reactions to the lessons. A formal debriefing session of participating teachers also occurred. All formal interviews of students and teachers were audio taped and transcribed.

Continuing the formative evaluation of materials, undergraduate and graduate student developers visited classrooms on a regular basis in order to interact with the students and see first hand how their software, experiments, and other activities were being used in the schools. Observers also took detailed notes concerning difficulties that students encountered when using the simulations or other materials. These notes were shared with THE OGAF developers. Classroom field trials resulted in the following improvements:

(i) We improved help messages to better meet student needs.

(ii) We discovered several "bugs" in the simulations that were not identified during small group trials.

(iii) The programmer responsible for *Fractal Coastline* discovered that students need to be able to save the coasts they generate. Students also told him they want to measure the fractal dimension of real coasts (e.g. Florida, California, Cape Cod, etc.). He added both features to his program.

(iv) We made improvements in the graphics and user interfaces.

(v) Teachers suggested numerous ways that the "hands-on" activities and experiments can be improved.

An issue which concerned many educators working on the project was whether the computer was used by students as a tool versus a toy. By giving students access to highly interactive simulations that give them an opportunity to test their ideas, the OGAF project hopes to demonstrate how computers are used by scientists to validate theories. While the computer is an important tool in scientific research, students often appeared to view computers as nothing more than a sophisticated toy. Classroom field trials have begun to identify factors that may contribute to either the "computer as tool" or "computer as toy" paradigms.

Observers noted that "hands-on" activities contribute to the "computer as tool" paradigm only when the activities are paired with interactive simulations that give students an immediate opportunity to test their theories concerning unexpected phenomena they observe. For example, in the electrodeposition experiment, students observed that a fractal aggregation of copper ions formed around an anode. The intricate branching structure of the aggregate surprised most students who expected a solid disk of copper to form instead. Observers reported that when students encountered this unexpected branching structure for the first time and had access to the computers, they used the *Aggregation Kit* program to model the results of the electrodeposition experiment. Like scientists at the Polymer Center, students used this simulation to determine how various microscopic parameters effect the shape of the fractal aggregate. In contrast, observers noted that the *Aggregation Kit* simulation was used more like a toy by students who tried the electrodeposition experiment and *Aggregation Kit* simulation on different days, had to go to a different room to use the simulation, or did not try the electrodeposition experiment at all.

Observers also noted that teaching styles and strategies appear to influence student conceptions of the computer as a tool or a toy. For example, in science classes where students are regularly given opportunities to make and test their ideas, observers found that students were more likely to use the computer as a tool. In more traditional science classes where students did not regularly get opportunities to explore, students appeared to use the computer as a toy. In addition, students whose teachers offered computer time as a reward for finishing other assignments appeared least likely to use simulations to make and test predictions.

H.3 Changing Classroom Dynamics

Based on the hundreds of hours of observation conducted in OGAF classroom by this evaluator and other educational researchers, we can say that any fear that computers in the classroom would produce isolation and alienation appears to be groundless. Instead, the use of computers as intended by the OGAF project has fostered new and closer patterns of teacher-student and student-student interaction.

The Newton South teacher reported that he knows a great deal more about his students now, having used OGAF.

> When I used OGAF, I didn't spend as much time in front of the class as before. Now I am working much more on an individual basis using the materials the way that we have set them up now. So I get to know students better as individuals as opposed to the way the class is going in general.

He compared this newfound experience getting to know individual students well in the classroom to his long time experience coaching.

> As a coach I spend three hours with my athletes every afternoon, but I only spend 50 minutes every day with my students. There is no way I am going to know somebody on the same level.... But it is amazing if you shift the way you teach how close you can

get to the kids in a reasonably short amount of time--when you shift from lecturer to someone that helps them support themselves in their learning. So what wound up happening was that if you are with them in small groups, with them while they are working on the computers, they get to ask you many questions about what is going on the screen, what is going on in the demonstrations, and you get a chance to see how they learn, the way that you didn't see it before.

The Belmont physics teacher attested to the claim made by the project director at the outset of the OGAF project. "Gene said that if used properly, OGAF should be like a graduate school model. I think my students behave much more like a bunch of graduate students than they do like high school students." He related a story to illustrate this point:

When I had to be away at a meeting, I left their assignment on the computer; it was a bunch of tasks they had to do, and I said to the sub: "The students know what to do, they'll be using the computers." When I came back, there was a pile of work they had done, and the sub said: 'All of the classes were good, but the first class ignored me!' He said: 'they just went right to the machines and worked. I had to chase after one group at the end of the bell.' So, my role has become, if I design the right things for them to do, and if the tasks are reasonably interesting, then the magnet of the technology, and their ability to work in collaborative groups and discuss their ideas and try to make sense out of them just runs the class."

He emphasized the centrality of group work in the proper use of the OGAF materials. To him, the computer screen...

instead of being something that someone passively looks like the lecture, becomes a focus for the students to discuss what they're observing, but they can discuss something that's changing and dynamic, rather than something on the board. I think the same technique could be used in a lecture if whoever was doing the lecture would provide the students the opportunity to actually discuss something that was presented on the board rather than absorb what was presented on the board. So I think the key to using the materials is groups.

Regarding optimal group size, he noted:

I used to think groups of two were the best, because of some things that I've read about having students discuss things in pairs, where one sort of silently listens to the other. What I've found is that three's work better. And, the thing that's nice about three is, in order to come to consensus, you need to do some convincing. You don't ever run into a situation where someone has to exert his will over the other group. They have to come to a mean. Students I think liked that and disliked that. They liked the fact that the majority of the time their evaluation was an evaluation of the group's understanding rather than their individual understanding, although I've tried to monitor both.

Referencing a constructivist view of human learning, the teacher said:

> One of the things that people talk about today is the notion of students making meaning for themselves. I think that not only do they make meaning for themselves, but that this group work reinforces and improves the kind of meaning that they eventually make.... I think the logs sort of verify that. (This teacher had his students keep electronic journals, or "logs" on the computer, and he gave feedback on their work.) I will try to throw some focus questions in there where I'll ask the kids not necessarily to reflect on something--although that comes out a lot. I'll ask them to talk about what something means, and the interesting thing about the OGAF materials, especially if you're judicious in the use of the workbooks, you're asking the kids to make meaning from things that are not trivial.
>
> They realize that when they first try to start making some meaning out of it--all the activities they've done and the programs they've worked with, and now they have to try to put this all together and the process of going through--this negotiation to makes sense out of something, even before we tied a name onto it, seems to be something they've found very exciting--the joy of putting it together. I was so concerned that the brighter students would object to working in a group, especially if someone in the group was not quite as able. That has not turned out to be the problem. It has been a very shared responsibility.

All of the master teachers cited the scheduling of OGAF classes in a typical 45-minute as a major constraint on the appropriate use of the materials. As the physics teacher in Belmont put it:

> Forth-five minutes really isn't enough time to use these. I would like to see double period blocks, so the kids, when they got into something, no matter how good kids are, it takes time for them to get up to speed, and time for them to wind down. That's the only complaint that I have, I have to try to sort of drop into a slot in the school learning session something which probably would work better if the students could just work for 8 hours. That's a constraint that's going to be much more difficult to get around.

H.4 New Patterns of Communication

Not only has the use of computers with OGAF fostered new patterns of teacher-student and student-student interaction, we have documented new patterns of communication including the use of learning logs and the reporting of research results to a community of scholars, much like the conduct of professional conferences for practicing scientists. Both the Newton South teacher and the Belmont teacher used computer learning logs to communicate with their students. These proved to be much less cumbersome than handwritten logs, which both of them had tried in the past.

The Belmont teacher had students work in groups of three, which he found to be the optimal number for promoting individual involvement as well as group consensus. Each group put all of the information that they did for the class on a computer, whether it be an analysis of a program or results of their experiment. The teacher provided comments to each group; he noted that

> What the logs do is give me the opportunity to spend time off-line, reflect on what they've done, and try to give them some creative points in the right direction. When you have a classroom of kids using these materials, the class itself become so chaotic, because not everyone is necessarily doing the same thing at the same time. You can't physically be all around the place, so you're moving around making sure there aren't any safety problems, trying to make sure that no one is really stuck. I see it as management time--making sure the students are managing their time effectively. As the unit progresses, that role becomes less and less, so that by the end of the unit, I almost have no job. All my time becomes off line, and I take a look at what they've done.... The learning logs give me the opportunity to reflect on what happened in the day, not just on one student or a class of thirty, but on each group of three. I know when they've hit a wall, and they say very honestly they're confused. I type in my remarks. An interesting thing is the kids seem to be more comforted by that than my going around and putting my hand over their shoulder and saying "Don't worry, you'll get this."

Reflecting on what they had learned with OGAF, as reported in their final entries on the learning logs, students had this to say:

> "Working in groups has been the best thing and the hardest thing. We learned from other people and most of all we learned about ourselves .... it created a conflict within me between taking control, which is often automatic or stepping aside to let the other people take the initiative"

> "I've learned a lot more in this class than just fractal stuff. I've learned new ways to learn....working with partners isn't always a stressful burden; it can help me learn better and it can be fun...computers can be used for much more than work processing."

> "The process of making proposals, designing experiments, having things fail, drawing our own conclusions and presenting our results gave a real sense of accomplishment and pride. By being totally responsible for the project, it became your own and we were willing to put in more than usual. Not only did we learn about fractals, we learned about science and ourselves."

> ".... instead of listening to a teacher talk all period, we had to learn about the subject on our own, which gave us a feeling of responsibility and self-confidence."

> "We think that this class is great. We like how we have to research on our own and learn from our investigations. We like exploring programs and the computer makes retrieving and recording data very easy. The class is fun and

interesting, overall we learn a great deal. It is amazing that we learned so much on our own."

"We learned very much about fractals so far, about the way they grow and the way they look. We were using computer and experiments to do so. Using the computer and working in groups was a new and nice experience."

"Discussing the randomness document was helpful because we have seen how certain we were in our knowledge and how much sense it makes (the randomness stuff especially). We have also seen some answers and explanations that are better than ours. Before we started the randomness document we already had an idea what this all was about, but by putting it in words, it was helpful in arranging all the ideas in our head. Also by working with a different group we gained different perspectives on some concepts, so we gained a better understanding."

"This class has been fun so far. We all like using the computer and being able to do graphs easily. In no other class have we utilized a computer as we have in this class."

"We concluded that this was a beneficial way of not only learning from others, but also enabling us to evaluate our work in a more objective manner. We now understand how fractional dimensions are calculated for dimensions between 1 and 2."

"Today we explored the Aggregation program. With this program we were able to compare aggregates formed by straight and random particle movement. We found that the aggregate created by random movement grew more slowly and its branches were spread out more than the straight movement aggregate. We thought the program was helpful for visualizing the molecular process by which the aggregate "grows". The aggregate in fact, "grows" the way a crowd of people congregate together (as if there were an accident.)"

"Today we had tons of fun with the Blaze program. By watching the program run alone at different forest densities we determined the critical density to be about 0.610. Below this value the fire will most likely not reach the other side of the screen and, above this value the fire almost always reaches the far side of the screen."

"Today we worked with GasketMeister and attempted to create the carpet square. We got close to making a square but we probably need more time to finish. We liked the program a lot!"

"This science course differs from other courses in many different ways. First of all, note taking is not part of the every day curriculum. Secondly, and most importantly, we use computer programs daily and this helps us see the progress that we are (are not) making. Also, we use cooperative and collaborative learning in class (this method is only used occasionally in other courses)."

> "It took us a while to figure out the "complexities" of Many Walkers but we probably have mastered the program. We want to do more on the Anthill program so this entry is short."

> "Well, as I am typing this, Paris is finishing off the scan of our aggregate and Tom is entering our data into Excel. Our ECD experiment was very successful and we managed to conduct the experiment unhitched. We hope to finish the analysis by Monday. Have a good weekend."

The physics teacher in Belmont had his students present the results of their research in electrodeposition using the forum of a research conference. Students embodied the format that scientists would use to address each other at a national convention. However one observer, himself a senior scientist, observed that the students were much kinder and more cordial to each other. In their learning logs, the five groups in his Physics II class reflected on their experience in these entries:

> "We loved the process of research, and presenting was fun. We felt likelearning this way is more realistic than most the things we do in highschool. Also it was fun because we got to study something we liked. Wewere thinking of spending more time doing research on population growth,and, since we both have time next semester, we would love to doindependent studies on it. We would like to cooperate with Paul T., andwe think that he will be interested, because he was the first person tomention that."

> "We presented our project today, and we think given the amount of work,we did a good job. Somehow, the presentation didn't quite seem tosatisfy or culminate the amount of work we put in. Maybe next year thestudents could draw an even larger audience and practice thepresentation to go smoother. We also feel we could have used a bit moretime, we found ourselves in here more than was sometimes convenient.Overall we appreciate the opportunity to work independently."

> "Thank you for making all of our overheads and helping us as much as youcould. It was interesting to see all the experiments that people cameup with and to see the results. Being able to think of our own project and do it for a week and then share the results was rewarding, eventhough it took us a long time to think of something worth doing. Itseems like everyone did really well on their projects and really gotinto them. A week and a couple days of class periods was enough time forus and looked like it was enough for everyone else, too. The freedom tostudy anything that interested us made for a wide variety of experimentswhich was interesting."

> "We enjoyed giving our presentation and we all agreed that we feltconfident in our presentation. In terms of the time constraints, yes, wefelt pressed for time, not in conducting our experiment but being shorton time to come up with concrete, feasible conclusions. Maybe givinggroups a time limit as to when the practical part of their experiment isfinished, that would enable groups to come

> up with better explanationsof their findings. We are such a great group, must we part and when?It's so funny that we've finally managed to function efficiently as agroup but we have to part. Oh well. We plan to finish the ResearchReport as soon as possible. When is the report due?"

> "We thought that the research process was good. We learned a lot aboutthe process of choosing a project, getting it accepted, and thenpresenting the idea. We think we would have liked to have a little moretime, it was hard to try and present results with only one measurementand then claim it as fact. We could have used about 3 or 4 more classperiods at least. The presentations were good. We were impressed withall the research projects. We think it is neat that we are going to get our results published!!! "

H.5 The Assessment Problem--What Are Students Learning?

All four of the master teachers recognized that assessment of student learning with the OGAF materials could not be done appropriately using traditional forms of assessment. The mathematics teacher had been reflecting on this question for some time:

> I don't know if it's hard because we don't understand the subject well enough ourselves to devise the appropriate assessment tools, or whether it's because the nature of the activities themselves is so different that traditional math and science assessment techniques are inappropriate. We math and science people have relied on methods that deal with hard numbers: "you got seven problems right and three wrong!" English and social studies people are used to a more subjective and holistic focus in their assessment techniques, but we're not--it's harder for us. So I don't know if it's the nature of the subject, or the way the subject is taught, or just our lack of sufficient knowledge of the material that's made it so hard for us to do the assessment. But I do know that every time I would devise a new assessment technique, its use would soon seem dissonant and artificial. I wasn't at all sure that after I had used whatever activity I had devised I would know any more about a kid's ability to understand the material than I did before I started. I wasn't at all convinced that there was any correlation at all between the kids' good performance on my assessment techniques and their actually getting something from the materials.

The evaluator questioned whether the teacher's familiarity with the material had deepened such that his ability to do assessment had changed for the better? The teacher replied:

> I'm getting better. This year I had the opportunity to spend a long period of time with the material, in the one course I did it with, the junior honors class, the same old reliable group. But that course itself was significantly restructured this year. It seems that the philosophy behind the BU chaos material is spreading through the rest of the curriculum. It's a lot more project-oriented, a lot more open-ended in structure; there's a lot more use of kids working in groups discovering and exploring, a lot more

> reference to real-life applications. More and more the traditional mathematical topics are finding connections in the BU material and are being taught through it, rather than separate from it. And that meant that this year I was actually able to give a couple of tests and quizzes and collect a couple of projects and grade them holistically and felt comfortable doing that. So it was the mix of traditional mathematics, which I could assess in more traditional ways, and the interaction with the bigger field that made it much more possible. I'm much less uncomfortable with that than I use to be.

Faced with the task of formal assessment of their students' learning, the three science teachers in their first year using OGAF attempted to use multiple choice tests or short answer constructed response formats. One of the teachers noted that there was "no assessment or evaluation built into the materials as they were first structured," so he tried to "build opportunities for the students to demonstrate that they developed the skill to use a particular program or to show how the program connects with what they've done." By the second year all three adapted more readily to the use of scientific reports by their students which incorporated sections on purpose, design, data collection, analysis, discussion, and implications. Graphs, charts, and images from the computer simulations were frequently incorporated into the students' reports. More extensive than traditional laboratory reports, the scientific papers were sometimes reported to each other in special sessions, much the way a community of scientists would present findings at a conference. The science teachers counted these papers as important components in the students' grades, but they still resorted to traditional methods of assessment when they taught the topics covered by standardized achievement tests.

As a specialist in testing and assessment with more than 25 years of university teaching and research in these areas, the evaluator had hoped to work with the science teachers in the development of new assessment techniques for use with the OGAF materials. However, the project budget could not support the summer work she would have liked with the teachers. (New assessments are slated to be developed as part of a new Instructional Materials Development grant for OGAF.)

Instead, the evaluator attempted to involve some of the scientists in the evaluation of student learning. One of the scientists who was particularly verbal and eager to see what students were learning with the OGAF materials worked with the evaluator in designing an interview protocol which he would use individually with randomly selected students. As a frequent visitor to the class, he was familiar with the students, and they in turn looked forward to his visits. He interviewed the students who had just completed a unit on aggregation which joined experiments on electrochemical deposition with simulations on the computer screen using the program called *Aggregation Kit*. Students had scanned the aggregate resulting from their ECD experiment, measured its fractal dimension, and compared the resulting images with those generated by the *Aggregation Kit* program. As he sat with them, one-on-one in front of a computer, the scientist asked the students focused as well as open ended questions and probed for depth of knowledge according to the answers they gave.

In his judgment most of the students could describe accurately the carriers of charge in an electrochemical cell when a voltage is applied across the solution and a current flows. As well they could identify what was being deposited on the cathode, were the material came from, and why, when they use zinc sulfate solution, the branches change color at the end, as the branches approach the anode. Most were able to describe as well what the sulfate ion was doing during the deposition experiment, why branch tip which is closer to the anode grows faster than a branch tip which was further away; and where the concentration of copper ions was lowest in the electrodeposition cell.

Asked to compare the ECD experiment to the Aggregation program, most of the students could describe the major differences between the simulation and the experiment, and what aspects of the experiment the simulation captured properly. In this the scientist saw evidence that the students were able to evaluate the computer program as a model which was less than ideal in simulating the actual experimental results which they witnessed. The scientist also inquired about important factors in determining a pattern's shape. He asked students to list factors which influenced the various patterns of aggregates which emerged from the electrodeposition experiment, the Hele-Shaw experiment, blowing up a balloon, and running the Aggregation simulation. Students were inconsistent in their ability to respond to this question, some very facile with prompt and fluent responses, others less certain, perhaps guessing.

Students' grasp of the random nature of the aggregation process was evident. The scientist asked whether the patterns generated by ECD were ordered or random structures. If students repeated the identical experiment would they expect to obtain an identical, similar, or very different structure. Asked to defend their answers with a short argument, students were able to say how phenomena which were random at a microscopic level gave rise to more orderly patterns on a macroscopic level. The scientist concluded the interviews by asking students to reconcile the apparent contradiction of making a prediction on a system governed by a random process. Most of the students did this to his satisfaction.

H.6 The Use of Concept Maps to Investigate Student Learning

Concept mapping is a technique which has been used to document student conceptions and conceptual change (Novak and Gowin, 1984). The technique is based on a theory of learning proposed by Ausubel which states that knowledge is comprised of concepts and propositions hierarchically arranged and linked in one's cognitive structure (Ausubel, Novak, and Hanesian, 1978). Educational researchers at the BU Polymer Center designed a study to investigate differences in the concept maps of experts, novices, and control subjects with respect to their understanding of fractals. The Belmont teacher's physics classes comprised the sample of novices who were taught about fractals using OGAF materials and control students who were given an article to read about fractals in the study by Shore, Hakerem, and Hickman (1993), "Using Concept Maps to Compare Expert and Novice Understanding of the Scientific Applications of Fractal Geometry. " Their concept maps were compared to those of experts who were university graduate students, post doctoral fellows, and scientists who conduct research on fractals in nature.

All participants in this study were trained in the approach outlined by Novak and Gowin (1984). They created visual representations of their cognitive structures. The novice and control groups completed concept maps on the first and last days that the eight-week OGAF unit was given to novice group, and they completed a third map six week later, thus yielding pretest, posttest and retention maps. The group of experts completed their maps at a weekly seminar, after they received instruction and practice in drawing concept maps. The maps were scored for the number of valid propositions, hierarchies, cross-links, and examples, following the scoring system recommended by Novak and Gowin. In their analysis of concept maps of the three groups, Shore and her colleagues reached several noteworthy conclusions:

(1) that high school science students are more likely to retain knowledge structures when they engage in inquiry-based, discovery learning guided by

apprenticeship teaching strategies than students who learn concepts by reading alone;

(2) that inquiry-based educational materials conceived and developed by active research scientists can help high school students assimilate key concepts and propositions defined by experts in the domain; and

(3) that high school student who use inquiry-based materials conceived by research scientists and developed by undergraduate science majors construct knowledge as hierarchically structured and integrated as experts in the domain.

Ausubel, Novak, and Hanesian (1978) claim that as novices gain new knowledge , their cognitive structures begin to show a hierarchy of relationships which move closer to those of experts in the discipline. Especially noteworthy among the findings from the study by Shore et al. was that novices demonstrated an understanding of fractals in nature which was indistinguishable from the experts. The high school students receiving instruction with OGAF materials and scientists at the Boston University Polymer Center constructed concept maps that had statistically equal numbers of propositions, levels of hierarchy, cross links, and examples.

H.7 Gender Differences in the Use of OGAF Materials

In their observations of OGAF class, the educational researchers, all of whom were female, took special note in their ethnographic field notes, of the classroom dynamics and social interaction patterns which took place in OGAF classes versus the non-OGAF classes which were taught by the master teachers. As well, the four master teachers, all of whom were male, were asked in several interviews, informal conversations, and debriefings to reflect on any gender differences they perceived in their classrooms.

The physics teacher from Belmont noted that "in his normal physics classes, the girls would raise their hands and the boys would blurt stuff out." But in his advanced class using the OGAF materials, "it is not an issue, because I use "creative randomness" to design the groups. "We have groups of three boys, or two girls and one boy, but never two boys and one girl...."

> When I've tried groups of three girls that doesn't seem to be as effective. When I've tried groups of two boys and a girl, that doesn't seem to be as effective. What I've noticed when it comes to mouse control this year, I've seen no difference between girls and boys, and in fact, if the boy tends to get a hold of the mouse, I've seen a situation where the girl unplugged it.
>
> The access to the technology has not been an issue, partially because of the fact that it's a group thing and their response that they put into their log is a group consensus. Maybe the one thing I think is that the female students tend to force consensus. They don't like to leave something dangling, where the boys would be more willing to do that. I think this forcing consensus tends to make them bring their ideas to some sort of closure..... To put it in a nutshell, the traditional description of how girls and boys interact in a class doesn't apply to my classroom because we're never in a situation where the girls are going to be raising their hands, because they're all working on tasks that are directed by the group.

One of the educational researchers who observed almost all of the OGAF classes which this teacher taught in the final two years of the project would concur with his assessment. She noted: "There were no overwhelming gender differences in his classes, no one raised his or her hand during discussion and everyone was involved at some point." However, contrary to the teacher's anecdote, she did note some other gender differences: "I witnessed the role of secretary often taken on by females in his classes; they recorded data while the boys manipulated computer and equipment. The girls also cleaned up more often."

All of the educational researchers who observed the Newton teacher in his first and second year using OGAF in his classes were struck by the classroom dynamics. He still leaned toward lecture and demonstration formats at that time, although he changed later. Yet, in lecture styled classes, he exhibited a striking contrast to the traditional teacher-student interaction patterns in which teachers, male or female, direct more attention and spend more time addressing the boys. In his class, in the words of one observer, "The girls were the most active and answered most of the questions while the boys rarely spoke unless spoken to." When we made this observation to the teacher, he responded by saying: "Maybe because that's because I've been coaching girls soccer for years. I know how to relate to them."

H.8 Effects on Minority Students

Some of the minority students that teachers identified as having either academic or discipline problems made noticeable achievements when they used the OGAF materials. Several anecdotal accounts taken from field notes of observers witnessing the same class sessions captured the enthusiasm, which could even be described as a "high", which some minority students mirrored as they used the *Blaze* and *Fractal Coastline* programs successfully and were able to tell their classmates how to do it. Teachers reported that these students became more interested in regular coursework, more prepared for class, and more involved in class discussions even after the *OGAF* pilot testing was completed. Observers and teachers hypothesized that new materials might be empowering disadvantaged students and increasing their confidence and their self esteem when they were able to use several of the programs successfully. Some observers suggested that visual learning may be more successful with these students. One minority student volunteered: "I liked using computers. I'm a much more visual learner." Other students reported feeling that the new materials put them on an equal footing with their academically stronger cohorts. Ellen (not her real name), a learning disabled Afro-American METCO student volunteered her impressions to an observer who related the following account from her notes:

> She turns to me and says I really like this stuff. I ask why. She says "because you don't need to know all the stuff for this that I haven't learned in all the other science classes." She says she just needs to know what she is learning in this unit. "That makes it not so hard as other sciences," she adds. I say "really?" She says "Yeah, it really is neat."

In fact, Ellen was one of the few freshman physical science students (disadvantaged or advantaged) who were able to correctly identify self similarity as a property of fractals after using the "Forest" program. On a written posttest several weeks later, she accurately described fractals as "a pattern within a pattern." Her success with the Polymer Center materials seems to have carried over to her other classes as well. In the formal debriefing session with the Weston teachers, one said "Ellen has a degree of self esteem that didn't exist five weeks ago, and it just showed up on an exam, in fact!" Ellen was not the only success story. Another Afro-American male, whom teachers described as withdrawn and angry, became an active participant in his physical science class. He came to class early, helped other students understand the simulations, and participated actively in class discussions.

H.9 Student Motivation with the OGAF Approach

Overall, there has been much positive reaction to OGAF materials. There is evidence that both advantaged and disadvantaged students enjoyed the *OGAF* materials. For example:

- Students came to class early and turned computers on right away. They had to be pulled away from computers at the start of class. Students also had to be pulled away from computers at the end of class.
- Students frequently asked if they could copy the software to take home.
- Four students in Weston Honors Chemistry chose to do their own variation on electrodeposition as their required project for the class.
- A group of Belmont Physics II students chose to do a long term project on fractal resistor networks.

Students who visited the Polymer Center to pilot test the simulations worked closely with science graduate students and post-docs. The experience of working with college students seems to have changed the way that some of the high school students view scientists. Marie, the Hispanic female who participated in the case studies, said that before working at the Polymer Center, she thought that most scientists were "crazy" and spent their time "mixing chemicals and blowing up things." Marie said her image of scientists came from movies and television portrayals and that her experience at Boston University gave her a more accurate idea of what scientists are really like and what they do.

I. Effects on Participating Teachers

I.1 Teaching Styles

Used as they are intended, the OGAF materials require a student-centered, hands-on, inquiry approach to instruction. A teacher who relies heavily on the lecture approach and functions as a dispenser of information may not be comfortable or effective with OGAF. A major concern for the project was how teachers would adapt to the use of the materials. Would they be able to tolerate uncertainty as their students pursued inquiry into areas which were at the cutting edge of science, where even top scientists may not know the answers?

The four OGAF master teachers, all of whom enjoyed reputations as very fine teachers, nonetheless were judged by our observers to embody a range of teaching styles. At the outset of the OGAF project, before any of the teachers were using the materials in their classroom, observers visited classes of the master teachers to make general assessment of their teaching styles. The physics teacher from Belmont was judged to be a very non-directive teacher. In response to students' questions, he would pose even more questions. As one of his student remarked to his lab partner, "Whenever you ask (that teacher) a question, he just gives you another question!" The teacher consciously prompted them to come up with the answers. "With the collective IQ in this room, I believe you can figure it out." But an observer who attended almost all of his class sessions with OGAF reported: "I sometimes saw students literally yelling at (that teacher) about his Socratic questions and his hands-off approach."

The chemistry teacher from Weston already taught in a fashion which was very compatible with the OGAF approach. His were student-centered classrooms, with lively discussion, and good humor. Frequently he addressed his students as "fellow scientists," and he was not above saying he did not know something if he did not know. The observers judged his skills at classroom management to be masterful.

The mathematics teacher from Weston and the chemistry teacher from Newton were deemed to employ more traditional teaching styles. They relied heavily on the lecture approach in very structured settings, in which the teacher dominated "talk time." Students did ask questions voluntarily, but comparatively infrequently, and only by raising their hands. We wondered how these four different teachers would employ the OGAF materials and whether their experience with OGAF would change these teachers' teaching styles.

The Belmont physics teacher became the focus of a study entitled "Applying Cognitive Apprenticeship Strategies To Curriculum Design and Instruction." Central to the OGAF project was the effort to adapt the mentoring model of graduate study in science at the university to the teaching and learning of science in the high school. Shore and her colleagues (1993) traced the evolution of the OGAF materials, informed by what is known as the cognitive apprenticeship model (Collins, Brown, & Holum, 1991) in three sequential trials of the fractal dimension unit by the Belmont physics teacher. In his first year of OGAF implementation, the Belmont teacher expressed his belief that students needed to learn to think for themselves and feel pride in being able to tackle different problems on their own. He often remarked to observers and to his students as well that they were smart enough to figure things out. He believed that by working together student could solve their problems. Unguided discovery commanded most of his class time. But in Year 2, the teacher became much more directed and offered students much more support and guidance. By Year 3, he was consciously adapting the OGAF approach to other units of his courses.

To quantify these changes, time coded field notes were examined to measure the frequency of various instructional strategies, including teacher guidance and student discovery. Following the paradigm outlined by Collins et al. (1991), teacher guidance was broken down into modeling, coaching and scaffolding, lecture and discussion. Further, coaching and scaffolding were broken down into two subcategories, teacher-initiated versus student-initiated support and information. He offered students detailed background information, demonstrated needed skills, and coached students as they attempted to model his example. Then, as students acquired the skills, he became less directive, monitoring students, circulating among the groups, offering suggestions, but not orders. In the second year trial, students began to act as independent investigators and the teacher gradually and spontaneously adopted the role of mentor. When the teacher was informed by observers that he had, in fact, moved toward the model of cognitive apprenticeship in his teaching, he seemed surprised, but on reflection, he concurred that he had indeed changed. These reflections are revealed in his musings during an interview:

> The match between my style of teaching and the one need to get most of the OGAF materials was a close one. ...I think it was close, but both using the OGAF materials and using technology has sort of driven my teaching style to an extreme that I would have never come to without using OGAF and the technology. I was always concerned with making the student the center of the learning, but I still felt the need to direct that learning specifically.
>
> It was a real enlightenment to me when one of the observers to the class pointed out that I had changed my style and I was approaching this technique called cognitive apprenticeship. Of course, when you're told you're doing something and didn't know you were doing it, it's very interesting, so I read some of the articles about it, and it made a lot of sense to me, and I could see myself moving in that direction. And, this year, I made it conscious. I said "well this is what I really want to do. I want this student to at the end of the course to be able to make this silver goblet, and my task is to provide the student with all the tools necessary and all the skills necessary to do that."

> As soon as I saw the OGAF materials as being a set of tools rather than a set of "knowledge bytes" so to speak, then the flow sort of became much more seamless than it had been before. The kids seem to enjoy it more, I was able to make sure that each test they took brought in one new element that made the test slightly more complex, so that when it finally came to the end and we did research, the research they did was meaningful instead of replication of something they'd already done. So, I think it was a good match in the beginning, but I think what has happened is the technology and the OGAF materials have by accident forced my style in a particular direction.
>
> When I realized that that was a direction and found out about it, it made me cognizant of that and it allowed me to then swing the direction even more, and the kids know it. It's real clear to the kids that when they come to class that their role is to do their job, and my role is to assist them whenever I can, not to the extent of saying "you're smart, you can figure that out." That was my style and I was taught that it was pedagogically sound to sort of when a student asks a question, throw responsibility back to the student. What I realize in most cases, the student is asking that question not because they're lazy, but because they really are having some difficulty, so I've modified that to sort of say "well, why don't you look here, here and here", and supply the resources.

The Belmont physics teacher also noted that increased familiarity with the OGAF materials and approaches was instrumental in shaping his effective use of the materials with his students.

> When the four of us involved in the project first started working with these things, I don't think we were comfortable enough with the connection between the real world and the hands-on experiments. I think it was a learning process for us, and we were able to learn along with the students. The fact that I can say to my students "hey I'm not an expert in this" doesn't mean I've never seen it before. The first year, when I said "I'm not an expert in this", what I meant is I don't have a clue of what any of this stuff means. I'm still trying to make sense out of this myself. Now, when I say that, what I really mean is "I really know where you're going to go, and I'm going to give you these series of things to do, and if you do these series of things I think you'll make some progress in this direction. And, if you don't agree with that, tell me and maybe I'll give you another path to take.
>
> So, it's not as if what happens in the classroom is not guided. It's very, very, rigidly guided. But it's rigidly guided in a global way, instead of being rigidly guided in a specific way. At any one particular time, groups of students can be doing different things, but they're all converging on some sort of understanding, and all of these little pieces are necessary to form that understanding...then there's some sort of assessment. It might be a presentation, it might be a document that they produce, and then that document is shared with the other groups, so that they not only can see what they have produced, but they can see what the other groups have produced, and really come to some sort of understanding. Does the other group see this the same way we did? We shared this experience.

This teacher has become so comfortable with the approach that he is adopting it in another unit in his class, the particle physics unit, which is not part of the OGAF collection.

The Weston chemistry teacher was judged by observers to have a teaching style very consistent with the intended use of the OGAF materials. Already he engaged in modeling, and coaching and scaffolding, with lively small and large group discussions, often student initiated. However, the direct, hands-on experience with new OGAF materials and computer simulation techniques seemed to rejuvenate this veteran teacher who had taught science for over thirty years. He explained to one of the observers that it excited him to be able to share his ideas for new experiments with the project staff. He said it made him feel valued. During an informal interview, an observer described the following conversation:

> (The Weston chemistry teacher) tells me that he used to think that he wanted to get totally away from teaching when he retired. He wanted to work with boats, but after this experience with our project he has given thoughts to staying with education in some capacity. He asked me if there was any possibility of doing some consulting work with the project when he retires. He says he knows that he will never teach the same after having this experience and he would like to share this with other teachers. He said: "This experience has put some excitement back into teaching for me."

In his use of the OGAF materials, the Weston chemistry teacher continued to employ the student-centered approach to instruction which he had used in the past. With OGAF however, there was even more emphasis on hands-on inquiry and investigation by students working in small groups. The teacher was comfortable in his familiar role of questioning students, prodding them with questions, and the giving direction when it was needed. But of any of the master teachers, he appeared to be the most timid about his command of the new science content reflected in some of the OGAF materials. When BU scientists visited his classes, he relied on them to teach his classes, and later he modeled some of what they did in his own teaching.

Observers saw the Newton chemistry teacher change over time from a very traditional teacher who relied heavily on lecture and demonstration to one who became more student centered and less directive. Clearly a reflective teacher, he gave up coaching two sports in order to become involved with the OGAF project--a weighty decision for him which he discussed with his family. In retrospect, he saw the deep commitment for kids in coaching and sports transferred to a different commitment to working with students in closer relationships in the classroom.

Observers who visited the Weston mathematics teacher's classes did not see a change in his traditional approach to teaching, which emphasized lecture with directed discussion. When his honors students were employing games, experiments, simulations, and computer programs in small groups, they appeared to be involved in on-task behavior, as they were in regular class time, his non-honors students even more so. While the Weston mathematics teacher appeared to continue using the teaching style which has worked well for him, he was very innovative in creating ways to introduce the OGAF units to his students. We saw him engage his students in learning experiences which he invented to fill the void in units which had viable computer programs but no hands-on component. One of the senior scientists witnessed this as well. Speaking of the four master teachers' experience with OGAF as experiments, he noted: We have only one mathematics experiment...and his is completely off scale." Asked what he meant by that, the scientist replied: "He's so good. He takes on materials and he can polish it and make it shine no matter what he's presenting."

One notable change in the Weston mathematics teacher was his view of the role of experiments in mathematics. At first, he was very leary, but in the second year of OGAF use, he had students doing demonstrations of diffusion in a mathematics class. Something he initially regarded as "chemistry," he came to see as "applied mathematics."

I.2 Preparing and Debriefing

All four teachers reported that they spent far more time preparing for OGAF classes than they did for their other classes. While they appear to have a lesser role in class time as students assume more responsibility for their own learning, the teachers in fact have to spend a great deal of time making sure that computers are loaded with the right software, making sure that the set-ups for experiments are available insufficient numbers, and especially dwelling on how to present the topics and problems in ways that capture student interest and develop their understanding of the issues and approaches to inquiry.

Above all, the teachers were themselves brand new to some of the topics and concepts, especially in their first year using OGAF, and they had to spend time learning the materials themselves, as well as thinking about how to teach the new concepts and approaches to their students. As one teacher put it: "All this is based on current research. The students could ask you a question that you couldn't answer. They could also ask you a question that there is no answer to; the researchers don't know. It's something they're still studying." As a teacher who had relied on the lecture method, who saw his students as a kind of audience, the lack of certainty produced some "jitters."

This constant reflection on how to incorporate the OGAF materials effectively in their classes led some of the teachers to create ingenious activities and approaches on their own, much to the delight of the project staff. In an effort to convey the idea of scaling more effectively to freshman physical science students, the mathematics teacher from Weston collected all kinds of containers whose dimensions and volume students had to measure. In a clever enhancement of the hands on activities to accompany the fractal coastline program, he had students flip coins to determine the direction of successive changes in angels formed by intersecting a straight line. As students drew the iterations, they saw how tedious the process became after several tries, but this hands-on experience led to a clearer understanding of what the fractal coastline program was doing when they witnessed controlled or rapid changes on the computer. To aid students' understanding of fractal dimension and the Von Koch curve, he made triangular shapes with hooks out of coat hangers which he used in class to demonstrate self-similarity and scaling.

I.3 Involvement Outside the Classroom--with Students

The two teachers who adopted the use of learning logs spent many more hours outside the classroom to respond to their students' self assessments, questions, and problems. The Belmont physics teacher called it "off-time coaching" when he's "on the computer trying to cajole them to get on task.... I think that's where the hard part comes in, because if they're doing something well, I want to make sure they know it, but if they're off track, or sort of let me down, I can let them know in a way that doesn't destroy them and is totally private, but still let them know that I was disappointed with their progress. I never get a negative from that. They say: "Well, we figured out a way to catch up."

All four teachers reported that some of their students returned to class after school or remained there after their last class of the day to continue working with the computers. In particular, the Newton chemistry teacher reported that he now sees some of his OGAF students 3 to 4 hours a day, not only in class, but during free periods and after school, when they work on the computers. He is "able to give his students a lot more feedback. It's fun, and it has become a kind of club. In several ways it is the place to hang out." Asked if it was exclusionary, he replied: "No, because they are bringing in their other friends that I don't teach, showing them this and showing them that." He observed that his students were able to create a context for the materials for the student that were not in his class. "It's very obvious that they do and they do a good job. Some of them make great teachers."

I.4 Involvement Outside the Classroom--with Colleagues from Other Schools, with Research Scientists and Professors

All four master teachers ranked their experience with the OGAF project as a major milestone in their careers, one that produced great satisfaction and professional growth, despite their already high levels of accomplishment. Collaboration in the OGAF project offered them opportunities to pursue educational development in intensive ways with outstanding teachers from other schools whom they did not know, and with research scientists who were uncharacteristically respectful of high school teachers and very receptive to their insights on teaching and learning. Much of this opportunity was concentrated in one summer.

At that time, the mathematics teacher in particular was very concerned with how pedagogically sound the OGAF materials were and that the units fit together conceptually. The evaluator had described to him what the co-director of the WAMNET project (another educational development project at the BU Polymer Center) called "development thresholds" for a program: the first threshold is passed when a program no longer crashes; the second when it is good-looking enough and user-friendly enough that we can be proud of its dissemination into the schools; the third when its documentation is completed and polished and its workbook finished. The mathematics teacher replied:

> Somewhere in there, there needs to be a level that indicates the program is pedagogically sound. This wouldn't refer to the internal consistency of the program,

> but rather to the external consistency; how does it relate to the other activities the teacher is going to have the kids doing? One important theme in all this for me is that computer activities are only one part of the larger thing that's happening.

The teacher went on to relate how this cohesion was achieved because the teachers had the opportunity to work together intensively and to interact with the scientists, programmers, and educational researchers:

> One of the most important things that happened last summer was how the teachers closely examined the fractal dimension program, bouncing it back and forth, trying to decide how pedagogically it had to operate in order to make sense to kids how it had to connect with the scientific concepts, with the way they understand the concepts, and with the laboratory experiments they were scheduled to do. It think it was clearly successful.
>
> Last year (in his high school) we had some students who did biological experiments in biology class, carried their experimental results down to the chemistry room, ran them through the scanner, and analyzed them with the fractal dimension program---completely on their own initiative! They had gotten to the point where they really saw the program as a tool that made sense to them and that they wanted to apply in other classes. When that young lady said she was calculating the fractal dimension for duckweed colonies, it really blew me away! None of us had ever mentioned that as a possible use for this tool, and yet she was using it to prepare a rather elaborate laboratory report that she was presenting to her teacher. 1-the biology teacher had nothing to do with OGAF, had nothing to do with the project at all, and didn't know anything about it....She had taken the Math IV Pre calculus class. That's where she ran into the material. But the tool got to the point where it was good and usable.

J. The Promotion of Interdisciplinary Science and Mathematics

J.1 Crossing Departmental Boundaries--What It Takes

One of the initial invitations to participate in OGAF was directed toward both a chemistry teacher and a physics teachers from the Weston High School. The chemistry teacher who was chairman of the science department advised us that his colleague in physics would not be able to work with us that year. The evaluator's description to the science chairman of the early OGAF materials and approaches including "probability and randomness" and "applications of advanced technology" prompted his reply: "That sounds like ...!" He named his colleague who chairman of mathematics department, who had long been interested in promoting the "math/science cross fertilization" as he put it. "Historically there has been a frustration among science teachers that their kids don't know the mathematics needed to do the science, and a frustration among math teachers that their kids can't see the scientific applicability of the math they're trying to teach them." We followed that advice and invoted both department chairmen to work with us.

Reflecting on the factors and circumstances that promoted their collaboration, the mathematics department chairman noted:

> Both (the science department chairman) and I have a lot of discretionary control over how we use our time and energy. As department heads we have reduced teaching loads, and our administrative responsibilities don't constitute a regular, day-to-day drain. There are periodic floods of obligation, but most days are not filled with tasks in which you have to be at a certain place at a certain time doing a specific thing. This was an important factor in our ability to take on this project and do the in-depth collaborative work necessary. (The science department chairman) was locked into only ten teaching periods a week. I was locked into only twelve. The usual teacher here is locked into twenty per week for teaching, plus two or three others that are supervisory.
>
> So we had a significant amount of time to work with. I took a group of students into BU to try out some of the ideas. They came back and talked to (the science department chairman) about it in his class. He saw that they were interested in it as well. He came into BU with us and saw more of the activities. It struck both of us that it was a good opportunity. It was also fortunate that the juniors I was teaching and the juniors Joe was teaching had a significant overlap, giving us a common group that we could focus in on and share ideas about....Then, when BU made the commitment to send a group of computers out to the school, we started to feel obligated to hold up our end of the deal. We knew they were coming and we knew we couldn't just store them in a closet.

The mathematics teacher was particularly eager to work with his colleague on the freshman physical science course.

> It excited me. I wanted to see as many different kids--as many different "flavors" as possible--interact with this stuff. I knew it would work well with Honors kids, but we needed to spread the wealth around and get as wide a range of kids involved with this stuff as possible. So we looked at the schedule of every period of the day and checked to see which math and science courses meeting during each period were ones we might be able to get involved with. That's the reason we ended up with such a wide range of classes involved with the program.

The science teacher in a separate interview offered the same kind of assessment:

> Last year when we decided to really make an investment in helping new people see how the stuff worked. We looked at our schedules, and (his colleague in mathematics)

> said if I took over the Math IV Honors class from (another, less experienced mathematics teachers) who was teaching it, I could work with the same students that you are working with in Honors Chemistry. And if I took my two Honors Geometry freshman courses, a number of those students are in the eighth or nineth grade Physical Science course. So we took the two 9th grade math sections and the two 9th grade Physical Sciences sections- in part so that we could deal with a different grade level altogether, but more specifically so that, with a given grade, we could deal with students with widely differing capabilities.
>
> We met almost daily during the whole month of January 1992. That whole month we spent some time nearly every day asking ourselves, What will we do? How shall we begin? How shall we begin with 9th graders? We tried to begin with the whole notion of self-similarity (with 9th graders!): different sized objects, the amount of water that they would hold, what their surface areas were- to see if there was any kind of trend at all among them. In my Chem class and in the Honors Math IV it was decided that I would change the time when I would introduce nuclear chemistry, which is normally near the end of the year, and put it at the beginning of the second semester, because then they could do electrical deposition. And I was concerned that my students still have what most colleges would expect them to have had in their high school chemistry course. I didn't want to abrogate too much, the topics I would normally teach them. So I could neatly slip electrical deposition into the course.

In addition to addressing these pedagogical and curricular issues, the two master teachers were concerned with how they could encourage their colleagues to adopt some of the OGAF units, when the content was unfamiliar to the teachers. Clearly staff development would be needed, but there was the additional challenge of working with concepts that extended beyond the teachers' knowledge of their discipline or even beyond their discipline. As the mathematics chairman noted:

> Teachers usually feel insecure whenever they have to go into subject areas that are unfamiliar to them. One of the spin-offs, from the math teachers' perspective, of the joint math-science workshops that we conducted recently was the discovery that many of the math teachers were anxious about their lack of confidence and familiarity with basic concepts in chemistry and physics. It's been a long time since most of them have had contact with those subject areas. And I can identify with that. I know often in my own case I'm not at all sure where a lot of the physics and chemistry is coining from and what's going on.
>
> I think one of the real potentials here in the teaming of math and science teachers is a clear message to the math teachers that it's OK if they don't completely understand all the science that's involved that's why the science teachers are there. It's OK for you to just contribute your mathematical expertise. If you don't know the mathematics you should be nervous, but not if you don't know the science! That's why it's so important to get at least two teachers involved together in this. It doesn't work if you just say to an isolated teacher "I want you to use more physics and chemistry in your teaching of mathematics."

J.2 The Need for Administrative Support

The evaluator noted that there had been some difficulties and misunderstandings in the teachers' efforts to incorporate OGAF materials in their curricula. She inquired of the mathematics chairman how we could make things easier in the future? In his judgment, the school system has to make a conscious investment: "Well, I don't see any way around the fact that the system has to be willing to release staff members from some of their regular responsibilities in order to spend time for this kind of growth." He had spent such a great deal of time in preparation for teaching with the OGAF materials that "In effect, I put all my other responsibilities on hold during that period of time much to my supervisor's dismay!"

Asked to reflect on the problems and challenges a year later he replied: "Well, there are things like teacher evaluation deadlines that have to be met. Although they were met, there was some anxiety that they were submitted very close to the deadline.... And the administration got anxious about that in this case, but I think that it was less significant than it may have seemed at the time."

J.3 Other Pitfalls and Constraints

In retrospect, the mathematics chairman and his colleague in science judged their initial efforts to involve another math teacher and another science teacher to be less sensitive than they might have been.

> "Although we went through the motions of asking these other teachers if they would like to have their classes participate in this activity, because we were the department heads I'm not sure how free those teachers felt to say no. A department head sends you an evaluation that says "here's a new, neat and interesting idea that would really be important to kids. Would you like your kids to have this opportunity? It's awfully hard for the teacher in that situation to say no. I think they felt they were on the sidelines from the very beginning.

In fact, the two department chairmen took over the classes of the other two teachers hoping that the teachers would stay in the classrooms, observe the process, and attempt to model them in the use of the OGAF materials. Instead, the other science teacher left the room, only to return at the conclusion of class to return homework assignments that were not OGAF related.

The mathematics chairman repeated the evaluator's question: "How could we have done that differently?

> If we had allowed more lead time, perhaps things would have been different. If we had sat down in September and decided which courses would participate, maybe that would have helped. Perhaps even better would have been to have started the previous April, before teachers were assigned their courses. If at that time we had said "here are some activities that we think will fit into these courses," then the teachers taking the teaching assignments would take them knowing that the activities were going to be a feature of it. The teachers would have had ample warning, and could have used the lead time to gain an understanding of the activities. They could even have taken the initiative to participate in the training coming into BU on the days provided and spending time with the material itself. As it was, they often stood on the sidelines in their own classrooms with the option of being totally inactive if they wanted. But all this is very hard. Were talking about beginning training in April for something that may not happen until the following January. Given the hectic pace of things at our school, that's unheard of!

J.4 Moving Toward Broader Levels of Involvement

The mathematics department chairman from Weston took several initiatives to expand interdisciplinary collaboration among mathematics and science educators, both within his own school system and throughout Eastern Massachusetts. As a member of the board of the Eastern Massachusetts Association of Mathematics Department Chairmen, he organized a meeting of mathematics and science department heads which was held at the BU Polymer Center on March 3, 1993.

> We met in the fall to plan activities for the year. I told them that there was this project at BU that was connecting math and science teachers together, and the members of the board all thought, "Gee, that sounds exciting!" They all thought it was something they should be doing but weren't doing. So it became one of our three activities for the year.

He was also the coordinator for the PALMS project in Weston, or "Project for the Advancement of Learning in Mathematics and Science," a state organization that is rethinking the whole math/science curriculum for K through 12 and is working under the auspices of the Massachusetts Department of Education.

> They were collecting data about math and science classes in all the schools: what kids were taking what classes and how well-trained the teachers were (in terms of professional background). And so their way of doing this was to appoint a P.A.L.M.S. coordinator in every school system, who would be responsible for gathering the data, going to meetings, and keeping up with the projects. So as the coordinator I begin to get stuff across my desk about various grant opportunities, and

one was a Commonwealth In-Service Institute Grant, a $5000.00 grant for in-service training. With the BU stuff in mind, I thought this sounded like a good opportunity to find some funds to compensate teachers for spending a Saturday; the idea was I wanted the science and math teachers to have a chance to get together and do some of the things Joe and I had done. We had tried in the past to do this as a part of departmental meetings at 3:00 o'clock in the afternoon, but people would be too tired; the short hour after school, a one-shot deal, just didn't do it for them. A few would get interested, but they would also get frustrated because they didn't have the conceptual background to see how things fit together. It just wasn't working.

So it struck me that a better way to do that was to have people come in on a Saturday, and spend the day. But I could only do that if I could find money to compensate them, because I wasn't going to ask them to do it for free. So this grant seemed a way to do that. So I wrote up the grant application and we were funded. It expanded from a one-day Saturday event to two afternoon sessions prior to the all-day Saturday. We obtained a computer using equipment funds. We managed to buy copies of a popular math/science book, *Does Cod Play Dice?*, for each participant to read, which gave us a common basis for discussion. We had funds for someone to come in from BU as a consultant to work with us; that was (the experimental physicist from BU).

The larger philosophical goal became let's set up math-science partnerships, so that people will begin to enter each other's classes. Let's break down that traditional isolation: 'this is my class and you can just observe from the back of the room." We wanted it to be possible for someone to come into a classroom and have a genuine role to play in what was going on. So we met two days after school for two and a half hours, and in those sessions I taught iteration of functions, chaos, fractals, and used some of the BU stuff we had written ourselves, and played some games and activities. And people had the opportunity to just muck around with the ideas for awhile.

There were two Weston High School math teachers and four Weston High School science teachers. And then they had the all-day Saturday workshop in which they did more of the science experiments, and saw how the concepts were developed through the experiments. So they got a chance to use the software, play the hands-on games, and do the experiments; they could see the three-pronged approach that's involved in the material. And since that time they've been meeting together in pairs, talking about their curriculums, talking about ways they see this material connecting, or other ideas connecting.

In addition, one of the science teachers involved in this workshop wrote a proposal for a summer workshop which was funded by the Town of Weston. (The school budget of the Town provides funds for curriculum development work in the summer. Proposals are reviewed by the school committee and superintendent.) The workshop involved the nucleus of the six math and science teachers involved in the previous workshop and four other teachers as well.

> The general focus is on math/science coordination. One of the strands will be further use of the BU material. Another strand will be coordinating our use of statistics, and use of the appropriate technology: calculators and Macintosh software. Since the math department is expanding use of calculators this year the science department wants to make use of them as well so that they'll have the common of understanding of what the tool can be used for and what kids have learned about it. But the real bottom line is that it's another opportunity for people from two different departments to spend time together talking about learning and teaching. The participants iii the Commonwealth Institute Grant have committed themselves to doing a joint activity in their classrooms next year. The system has committed itself to releasing those teachers from their teaching duties during that common period, so that if a math teacher is working with a chemistry teacher and that means the math teacher is going to have to be in the chemistry teacher's class for two or three periods, the system is committed providing substitutes or using the department heads as substitutes! And the teachers see that as a commitment that they are obligated to fulfill, so I'm pretty confident it will happen.

Asked to what extent are the BU materials a catalyst in that coordination, the Weston mathematics chairman replied:

> Oh, very much so! What you saw with the math and science department heads was that very quickly they began to admit to each other they didn't know what was going on. It was a new idea for them. It wasn't something they had seen before. And so they had to approach it on an equal footing. Neither of them was the acknowledged expert in the field, and so they both approached it as students to try to learn stuff. And that happened here as well. It was an area that was neutral enough to both turfs, and yet connected enough to both turfs, that it struck a natural interest among the people involved and yet they didn't feel guilty about not being an expert. And that was very necessary. An unevenness, where one person knows a lot more than the other, has been the death knell of an awful lot of activities. When teachers come together, it is very hard for somebody to be the weak partner, especially when you're working in a system where expertise and knowledge is highly valued.

K. Effects on Other Participants in the Development Process

Additional findings pertain to the social dynamic influenced by the OGAF project, among the project staff members themselves, not just the participating teachers, and the high school students whose responses have been given in earlier sections. While the evidence of the impact on the project staff is anecdotal in nature, the observations are too important to ignore.

K.1 Senior Scientists

The Project Director/Principal Investigator for the OGAF Project was considered by all participants to be the driving force behind the project. Of course, he could not have seen the project through to completion without the help of many other very competent and dedicated people. But why would a world-class scientist invest time in educational development for the high school level? The evaluator asked him this question directly: Why did you do it? He responded: "For two reasons. One is altruism. Everyone of us who has benefited from education in this country has some part to repay.... The other reason is that no one has ever tried it before.... I get kicks out of doing things that have never been done before." The principal source of satisfaction which he derived from the project was seeing it completed. " Most projects do not get done, because it doesn't work or what ever.... Most won't result in more than an annual report. So the satisfaction for me is that it got done and that it works." It was also very important that he did not have to sacrifice his research career.

> Individuals, other than myself, worked together so well, therefore I did not have to stop my research career in order to see this through during the past five years. If I had to stop myself research career, it would have been much worse. There have been scientists who have gone into education, and to my knowledge, all of them have been required of necessity to stop their research careers. I can only assume that this is because either they wanted to stop or, more likely, because they found it to take all their time to do what (our Project Manager) does which is to coordinate everything, which would take all my time because it took away all his time. So it was fortunate that we had a group of individuals who are willing to do basically everything.

The project's co-director was well respected as both a physicist and an educator. The author of well-known and widely disseminated textbooks on quantum mechanics and relativity, he said that he went to MIT "to write a textbook back when you used to get money for curriculum in college--the good old days." Refering to the name of an old TV series, he saw himself as "Have Gun--Will Travel," disposed to taking on a variety of roles and responsibilities for the project according to what was needed most. He functioned as a close advisor to the project director, but he also did computer programming along side undergraduate work study students. With characteristic modesty he noted: "It would probably be a mistake to have people like me do professional programming because the undergraduate are so much better at producing the real stuff--they're the real pros. On the other hand, I think of myself as trying to do programming to figure out what the programs are and the intellectual problems, and the research problems." Clearly, the co-director was held in high esteem by everyone conntected with the project, from the director on down.

Seen by many project participants to be a jack-of-all-trades, the co-director mused: "Well, I think it's sort of a bad idea to be classifiable because you're too disposable. Specialization sort of puts you in a box." Interviewed on his birthday, he announced: "Today I'm 61, and I feel as you get older and have more experience you ought to take more chances. I consider my life to have included a lot of chances. Since I don't know what security means anyway (he spent 25 years untenured at MIT on rolling three-year contracts), this seems to be very satisfying....

> I have learned a lot. The way I learned things was to write it down so that other people could figure it out as well. Because I was doing the aggregation workbook I finally figured it out what fractal dimension means. The first day that I walked in people could have told me what a fractal dimension means but I wouldn't have got it. It's taken me all this time for me to be pretty secure enough so that I can explain it to you. The setting allows me to digest it the way I need to digest it and this helps me explain it to other people. So in that sense I learned a great amount of science--understanding the way order grows out of chaos in so many different settings. There is always something going on to lead me to say aha by the end of the day.

Still another senior scientist was crucial to the success of the OGAF project. Rarely do practicing senior scientists become involved in high school education. Fewer still actually spend any time in high school classrooms. The experimental physicist who joined the project in 1990 was a notable exception; in the judgment of this evaluator and several of her colleagues, his growth as an educator was profound over the course of the OGAF Project. The classroom teachers noticed it as well:

> I recall at that time that (the esperimental physicist's) presentation went way over the heads of practically everybody. We spoke to him afterwards, and said: "This is a very different audience than you are dealing with when you deal with graduate students at BU." And it is his involvement with us now that is so helpful and so positive. My students have had numerous contacts with him over this past year, and they always rave about how much they enjoy his presentations, about how clear they are, and they love (that physicist's) enthusiasm. So his role has made a big difference in what we've done here.

Addressing this scientist, the evaluator noted that it is very unusual for a research scientist at a university to become involved in educational development. She inquired: "Why did you do it? How did we get you here from Michigan, and why on earth would you come to do this work?" He replied:

The bottom line on this has nothing to do with nobility or anything, it was money. The money ran out at Michigan. My wife had gotten a post doctoral position in Boston and I had to look for a job.... Now here was a real problem because as a physicist I always assumed that when I left research I would have to sell my soul and simply do defense work, but I would be appropriately well paid. Well, my good luck or bad luck was, there was no defense work to be had either, since the defense industry was crashing at that time, and during my long search,... one physicist said "well I know somebody who is doing education work... but I don't know if you'd be interested in that." I had to stop and I had to think very hard....

I decided that if there was anything else than research that really turned me on or something that certainly got me madder than research, it was the state of education. Because I realized I could become so emotionally involved with doing education right that I decided... I should follow up on this as a possible job..... By complete coincidence Gene had just gotten the grant from OGAF. If he had not, there probably would not have been a slot anywhere for me in Boston to education work.... When I describe myself to other people and other physicists who are looking about how to get into education I say very frankly the niche that I'm filling is terribly small. It is no bigger than one person size and I just happened to be the right person at the right time because I had done exactly the kind of research that Gene needed to support his work. And so the other way I say it is once again my life seems to put me in the situation of doing jobs that I like, whether I'm being paid enough to do it or not or whether I was expecting to that kind of job or not. So I get to do something that I enjoy very much for reasons I never expected.

Asked to assess the impact been on himself personally and professionally, the scientist was quick to point out that "it takes so much time to do the education work that I have very little time left for straight research." He did expect to pay a price for that in his career.

Oh, for sure! But the question is what career. It's not clear what's necessary right now in the United States for scientists to maintain a career. All I have to do is look around. I had an interview done with me by the American Physical Society as a physicist who found an alternative career path. That's what I consider this. I try to maintain my research connections, I try to do research on the side and basically that's what it has to come done to, but most of my time has to be dedicated towards the education work. Quite simply because doing that job right requires a heck of alot of time, a heck of alot of effort. Education work is after all an experimental science, that's the other I've decided, because you don't know what works until you try it.

K.2 Project Manager

Another critical member of the OGAF project team was the young man who served as full-time Project Manager. As an undergraduate student, he had been an academic advisee of the project director. With a new baccalaureate degree in physics and bioengineering, he was willing to delay full-time graduate studies in order to continue working with his mentor on the OGAF project. Asked what impact has it had on you personally and professionally, he replied :

> "I actually enjoy being at the frontier....I have become much more interested in technical innovations as opposed to doing pure research. Previously when I was a student, I used the computer as a tool to do something but really what was exciting was the science.... But now I have become much more aware that the technology is exciting also and I have been trying to work with that a little bit. So I don't know what is going to happen at the end of the picture. I don't if I am willing to continue in this direction in working with technology.... But I do feel that I have options open to me. And I have choices to make.

Clearly his work on the OGAF project "has dramatically changed how I do things." Asked if he had any regrets, he replied emphatically: "No. No regrets at all. It has just changed things." Now he viewed himself at the cutting edge of a whole new endeavor.

> It is hard in science to get the feeling that your a pioneer in something because everyone else is doing it, unless you are a Noble Prize winner.... But in this area of computer technology, especially technology applied to education, is such a new field the feeling of being a pioneer in something is just like getting a high. There is something attractive about it, something that draws me.

The OGAF project caused him to reflect on the need to reform science education and the potential which advanced technology held for addressing this need in a dramatic way. "I like what we are doing. I think that the country as a whole needs this." But he was very critical of other efforts which were underway nationally which had been showcased at a recent computer fare held in Boston. "I think that most of what I see out there I don't like. I think that it is too bad. I think that there are a great many smart people out there. But I don't think a lot of them are spending time on education. Education is getting the shaft." He was especially critical of the preponderance of tutorials among the software which was being marketed.

> "Everything is tutorial because you don't have people who are knowledgeable about simulations and science writing these things. You don't have people who are experts in many of these things. You have people who are may be just technology oriented. Or you have people who are just educationally oriented. You don't have people who are scientists. And that is a shame. I don't know why that is actually, given sorry state of jobs in physics and science in general."

K.3 Post Doctoral Fellow

The post doctoral fellow who supervised the work of the undergraduate programmers and consulted with them regularly to be sure that the computer simulations were scientifically accurate immigrated to the United States in May, 1990 from his native Russia. He had taken his Ph.D. in physics from the University of Lenningrad. His dissertation focused on the application of random walks to polymer science, a topic that was at the heart of current research of the Polymer Center and the OGAF project. Starting as a programmer with the OGAF project, this "post-doc" took on the responsibility of teaching new undergraduate students who were novice programmers how to use the Macintosh tool box. As he grew in expertise in programming, and consulted with the professional staff and the teachers about the scientific and educational goals of the programs, he became one of the principal decision makers about whether to continue investing time and talent in the development of a unit. He also visited the schools "about probably 10 times." Clearly he had a keen understanding of what the OGAF project was all about:

> The goal of the project I think is to show high school students what science is all about. It is not about learning about some rules which were discovered centuries ago, but to be the first person that observed some new phenomenon. To be the first . To be an explorer. To be the first person in an unknown land. I think that this is what our project is trying to teach students, how to explore new models probably without even appropriate knowledge for this. When the scientists start to study new phenomenon usually he doesn't have appropriate knowledge. This knowledge comes to him only in the process of doing science.

In his view, participation in an educational project will help scientists in their academic careers. He cited an example from his own experience with the Polymer Unit and its paper tearing experiment:

> Scientists have to devote a reasonable percentage of their time not for science but for education, but it is not sometimes bad for science. Because usually when you are trying to explain it in very simple terms you can probably understand some problems even better. Some of our scientific ideas came from our participation in high school education. And one of these examples is the rough surfaces phenomenon, which we all know is the OGAF project. This unit was started with very childish experiments with paper towels and coffee. And out of this, in parallel with education, grew new scientific results. And we published several papers which were started by this educational project. (*Really! So the educational involvement has brought about some scientific inquires?*) Yes absolutely. It has helped to understand some problems in a simple way.

K.4 Graduate Students

Some of the doctoral students in physics have said that working half time for the Polymer Center education projects has influenced their career goals. For example, one student became interested in adult literacy and took courses in the School of Education. Another doctoral student, who planed to work in industry and continue her research on polymers, also hoped to continue developing materials for high school students. Still another Ph.D. candidates approached one of the educational researchers to say "I don't want a scientific research career for the rest of my life. The only time I have been happy here in this department is in my TA role. I want to do something more socially relevant with my live." He looked to education as something he might join with his career in physics. However, upon completing their Ph.D.s, most of the new degree recipients took jobs in industry. One who left to become a post-doc at another university has remained in close contact with the Polymer Center. With a view toward returning to a university in his home province of Nova Scotia, he envisions room in his career for continued involvement in science education.

K.5 Undergraduate Programmers

The post doctoral fellow who supervised undergraduate programmers in their development of OGAF programs for their technical qualify and scientific accuracy directed their initial efforts toward the application of random walks to polymer products, since his Ph.D. thesis was in this area. In terms of their commitment and contribution to the project, he judged their success rate to be one in seven, or about 15%. Of the 7 to 10 undergraduates who came to the Project each year in September, only one or two remained with the project. They were the most interested and the most capable, who became accomplished programmers.

Of the handful whom we all concurred were the most effective, two in successive years received "student employee of the year" awards in a university of 28,000 students with a sizable work-study population. It was also noteworthy that the accomplished programmers were eager to visit the high school classrooms to see their programs in action at the hands of high school students. Not only did the programmers find this experience very gratifying, the high school students expressed surprise and admiration that individuals not much older than themselves could develop such an engaging program. The interaction between the students at these two levels was also interesting--the undergraduate programs receiving praise along with well intention suggestions from the high school students on how to improve the program.

L. The Model of Development--Lessons Learned

L.1 The Talent and Resources Needed

The key factor in the success of the OGAF project according to virtually all participants was the Principal Investigator himself. Without his initiative, vision, and energy, the OGAF project would not have come to fruition. He is described as "a person who really loves science, loves education, and loves people. He really wanted to make some kind of good thing out of his science to help people."

Another key person named by many participants in a second breath was the Co-Principal Investigator. One of the international members of the project staff referred to him as a "famous educator" whom he first learned about as a child, and whose physics textbooks were translated into Russian. With a command of the physics, knowledge of programming, experience as a textbook author, and instincts of an educator, the Co-PI was able to field a wide variety of responsibilities and made himself indispensable to the project. His ability to span so many tasks and relate so effectively with everyone from the project director to the undergraduate programmers enable him to serve as a bridge between the participants and the project chief who was busy with so many other things besides OGAF.

The young man who served as Project Manager was willing to delay full-time graduate studies in order to continue working with his mentor on the OGAF project. In effect, it was the Project Manager who enabled the Princvipal Investigator to continue his career as a research scientist while leading the OGAF Project. The Project Manager to an extent buffered the scientist from administrative details by taking on a number of management responsibilities. And, like the Co-PI, he was adept at programming, a good writer, and knowledgeable about the physics content of the project. Thus he was able to assume a variety of roles as the need arose.

The Principal Investigator was an magnet to the cadre of gifted young doctoral students he attracted for graduate studies. Unlike most professors in physics who might have one or two students as advisees, the Principal Investigator had ten or more full-time doctoral students in a given year. Instead of assuming teaching or laboratory assistantships for their stipends, several of these students were obliged to work on the OGAF project. While it was difficult to extract a commitment from a disinterested student, those who were committed to the OGAF project brought to it great talent as programmers and scientists.

Not only was the Principal Investigator a magnet for doctoral students, he also commanded a world-wide network of international colleagues, many of whom he attracted to the project, some of whom were very helpful as constants to the educational directions of the project and/or to specific programs.

The project also relied on undergraduate programmers whose work study stipends were a tiny fraction of what would have been required to pay professional programmers. The professional staff of the project is still in dispute about whether the use of undergraduate programmers versus professionals was the right direction to take. A handful of the undergraduates proved to be very effective, producing programs that have commanded the attention of teachers, students, and advisors to the project. However, for every one of these success stories, there were five or six whose work was not useful.

People with talent and commitment were the key ingredients for the success of the project. However, physical resources were factors as well. Yet again, it was people who were instrumental in acquiring and committing these resources. The Principal Investigator and his team were able to gain equipment grants from Apple Computer Corporation, Digital Equipment Corporation, International Business Machines, and Silicon Graphics, Inc. The Director of the Science and Mathematics Education Center at the University, who was himself an astrophysicist and close colleague of the OGAF Principal Investigator, was instrumental in gaining approval from the Office of the Provost for the allocation of attractive spaces and furnishings for computer rooms and for the experimental laboratory where the development work of the project was undertaken.

L.2 Replicability

Most members of the professional staff of the project thought that the model of OGAF development could be replicated at other universities--if they could find the right people. Practicing scientists would "have to devote a reasonable percentage of the time, not for science but for education." The vision and commitment of the project director would be key. But the OGAF Principal Investigator did not relish his experience with the management of the project. "Everything was negative. This took time from research, it took subconscious time, meaning that as a researcher I had to account for the time actually doing the work and the time thinking about the project."

Asked if he would do it again, the Principal Investigator replied emphatically: "No! Absolutely not! I put in my time for the most undesired activities you could imagine. To be very honest I did not enjoy any of this except that I got it done." (*Has it been worth it?)* "Don't ask me now, it's too soon."

Despite these negative feelings for the demands of project management and the taxation the project required from his research, the Principal Investigator still thinks that it is important that university scientists collaborate in this kind of science education development enterprise. Asked what incentive should the National Science Foundation or other potential sponsors provide, the Principal Investigator advised:

> One thing is to require it, plain and simple. No physics teacher I know is required (to participate in educational development). What I did was to show that it could be done, but at a great expense. Now, if it was required, then certain steps can be made. I don't think it's unrealistic. This would be more beneficial than teaching a graduate class.

In addition to the incentive and the influence that the National Science Foundation could have by requiring participation in educational development as a part of their research grant program, he thought universities could make a similar requirement:

> Universities have faculties that work between 40 and 80 hours per week, which adds up to a very small fraction on teaching. Carving out 5-10 hours a week for this kind of a project is not very much. They should find 5% or so of their faculties who are capable of doing this type of work and let them do it instead of teaching or add it on. This is very much in the interest of the university--this would attract the students and the income. I think that if it is desirable to do something, then it can happen. We have to recognized that high school kids are the most precious resources we have...children in general... high school in particular because we have to help them find science

especially into college.

M. The Future of OGAF-- The Future of High School Science

Asked to judge the impact of OGAF on science education at the high school, the Principal Investigator would prefer to leave that to others who "can answer better than I...who know more about education." However, he noted that "we have shown that by using technology we can bridge or narrow the gap between high school education and current scientific research. In addition, we can place the students in a situation like graduate students experience when they embark upon research."

Still he would agree with the evaluator that "in a sense we are done, but we are not done. If we were to leave things the way they are, then there would be a very short half-life OGAF." Significant additional work needs to be done in two areas for the OGAF project to realize its potential: the development of instructional materials and teacher training.

M.1 Instructional Materials Development

At the completion of the five-year grant period for the OGAF project, several crucial tasks remained. The last three of the six units shown in Table 1 were still in the beta stage of development. Unlike the first three units which had seen extensive field testing and which were the beneficiaries of close teacher scrutiny, the last three were incomplete. Hands-on activities and/or experiments needed to be created to compliment the computer program. Not only scientists but teachers as well need to examine the newer units to envision where they can fit into the high school mathematics and science curriculum and how they can be used in effective ways in the classroom, ideally with the kind of field testing the first three units received.

All of the units need to be examined from the point of view of assessment. Specialists in assessment should work with the teachers and scientists to develop performance appraisals of the complex problem solving outcomes which the units are designed to foster. Traditional paper and pencil tests and short answer constructed response items are inherently limited and do not have the potential to tap the higher learning and the connections we hope the students are making as they pursue scientific modeling and discovery.

A pilot edition of a workbook entitled *Fractals in Science* has been written and circulated among the project's professional staff including the scientists, educators, consultants and master teachers. It was used during the Summer of 1994 with OGAF teachers-in-training, but clearly the work was very preliminary and needs continued development, critique, and rewriting. A revised version was used during the 1995 summer workshop. Continuing revision of the workbook and fuller development of all units is being supported by a new Instructional Materials Development grant from NSF which was awarded in 1995.

In addition, the evaluator would like to reiterate suggestions for the use of video and still photography which will aid the continued use and wider dissemination of OGAF. These images should be collected on a compact disc to accompany the textbook materials. The following list is illustrative but not exhaustive of the needs and opportunities for research, teacher training, and dissemination of OGAF materials:

- Video footage of all experiments, including the laboratory set-up from raw materials;
- A library of static fractal patterns which abound in nature: including lightening bolts, river deltas, coastlines, mountain ranges, nerve cells, termite tunnels, bacteria cultures, root systems, galactic distributions, forest growth and burning, lungs, the nervous and cardiovascular systems, and even cauliflower and broccoli.
- A library of dynamic fractal images including footage from NASA, WGBH Public Television, DOE, and IGS;
- Photos or videos showing the scaling properties of examples of fractals in nature, including broccoli, lightening, termite colonies, dendrites, and others;
- Videos of experiments in progress including electro-chemical deposition with varying chemicals ($CuSO_4$ and $ZnSO_4$), molarities, and currents;
- Film footage of the use of the OGAF units in classrooms, including the hands-on activities, experiments, and computer simulations;
- Footage of the collaboration among graduate students and scientists in the research and discussions which inspired OGAF in the first place.

Fortunately, the OGAF project team has won continued support from the National Science Foundation to see this investment through to a stable and hopefully self-sustaining level of development. Continued development and documentation is needed for wider dissemination. Without it, the prodigious efforts will be lost to memory.

M.2 Teacher Training

Teacher training is a critical cornerstone in any serious efforts toward educational reform, but this especially so for the OGAF Project. The OGAF approach to science education dictates a new role for teachers, focuses on new content at the cutting edge of scientific research, and harnesses the power and speed of advanced technology. Even the most outstanding of high school science teachers today cannot be expected to employ the OGAF approach without guidance. Indeed the distribution of computer programs and other materials without teacher training would be a fool's errand.

An expert in science teacher preparation at the Boston University School of Education has joined the OGAF Principal Investigator in securing a new grant from the National Science Foundation's Teacher Preparation and Enhancement program. The grant will be used to provide intensive summer workshops for high school science teachers over the next three years. The plan calls for cycles of training for 32 teachers each summer, with participants chosen from a national pool of applicants, and 10 resource agents selected from among the most successful workshop participants who will lead training of still more teachers in their local areas. The four master teachers who have worked on the OGAF project since its inception carry the primary instructional role during the summer sessions. The availability of the workshops has been announced through science teacher's own professional organizations. Qualified applicants who cannot be accommodated in the forthcoming workshop are guaranteed a spot in the subsequent year's workshop.

Another feature of the training plan is continued follow-up during the school year as the teachers new to OGAF attempt to implement the model in their own classrooms. This follow-up is accomplished primarily through telecommunication, enabling the project staff to use America on Line to send and receive electronic mail communications from teachers. The teachers can seek guidance on problems they encounter and offer reports of their progress. The project staffers can send suggestions and provide updates of software on a monthly basis.

The first of the three sessions was held in July, 1994. More than 200 requests for information produced more than 50 applicants, 32 of whom were chosen to participate in the first round of training. Daily written feedback from the teachers was consistently quite positive. A select, self-renewing group to begin with, they seemed especially appreciative of the opportunities to work across interdisciplinary lines, as the materials were intended to be used. As the co-director put it: "We had someone in physics talking about doing an aggregation problem one way, the chemistry person talking about the same thing another way, and the biology teacher still another way."

The teachers were expecting to be faced with a lot of new science in the workshop, but they were surprised to get as well "a lot of new pedagogy." The workshop leaders were careful to provide a pedagogical rationale for urging teachers to change the way they tech and adopt the OGAF approach. To this end, their discussions included consideration of the model of cognitive apprenticeship, and the use of learning logs and concept maps in the assessment of student learning.

The future of the OGAF project appears hopeful because enlightened people have responded to and supported the need for continued development and refinement of the OGAF materials and for teacher training. To promote effective dissemination of OGAF beyond the termination of the two new initiatives in IMD and TPE, it will be important that a portion of the cost charged for OGAF materials be ear marked for the maintenance of a help-line--some means by which members of the OGAF project team can respond to requests for assistance from teachers in the field and can update teachers with improvements to the OGAF materials.

N. Dissemination

Efforts have been made to disseminate OGAF materials through traditional means such as publications and presentations at professional conferences. These publications and presentations are cited in the following section. Additional means for dissemination of OGAF have involved the use of electronic mail, the Internet, and most especially the World Wide Web. The project manager collaborated with the systems manager hired to oversee computer operations supporting all of the NSF grants which the project team is working on. Together they created a very attractive, eye catching World Wide Web Home Page for the BU Polymer Center and offered in its menu ways to access the Center's educational development projects, including OGAF. Statistics on Web site activity for the Polymer Center indicate that during a three month period alone, tens of thousands of inquiries have been made about these projects, from all over the world, and from a wide range of organizations: colleges and universities across the United States and throughout the world; a host of military and government organizations, corporations and businesses which are part of the scientific community, and of course schools.

N.1 Presentations and Publications About OGAF.

Erickson, M.J., Hakerem, G. & Shore, L.S. (1992). *Student Conceptions of Randomness.* Paper presented at the Annual Meeting of the American Association of Physics Teachers.

Erickson, M.J., Shann, M.H. & Shore, L.S. (1993). *Introducing Computers into High School Science and Mathematics Classrooms: The Effect on Human Interactions.* Poster session presented at the Annual Meeting of the American Educational Research Association, Atlanta.

Erickson, M.J. & Shore, L.S. *Computer Use in High School Science Classrooms: The Effect on Human Interactions.* Contributed paper presented at the Annual Meeting of the National Association of Research in Science Teaching, 1993. (An edited version of this has been submitted to the journal *Educational Technology: Research and Development.*)

Hakerem, G., Erickson, M.J. & Shore, L.S. (1992). *The Computer as Tool or Toy.* Contributed paper presented at the annual meeting of the American Association of Physics Teachers.

Hickman, P. (1993, March). *Fractals in the High School Science Classroom.* Workshop presented at the Annual Meeting of the National Science Teachers' Association, Kansas City.

Hickman, P. (1993, January). *Fractals in the High School Science Classroom.* Workshop presented at the Winter Meeting of the American Association of Physics Teachers, New Orleans.

Hickman, P. (1992, November). *On Growth and Form: Fractals, Randomness and High Speed Computing in the High School Science Classroom.* Workshop presented at the Regional Meeting of the National Science Teachers' Association New York.

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Shore, L.S., Erickson, M.J., Garik, P., Hickman, P., Stanley, H.E., Taylor, E.T., Trunfio, P. Learning Fractals by "Doing Science": Applying Cognitive Apprenticeship Strategies to Curriculum Design and Instruction. *Interactive Learning Environments.* In press.

Shore, L.S., Hakerem, G. & Hickman, P. (1993). *Using Concept Maps to Compare Expert and Novice Understanding of the Scientific Application of Fractal Geometry.* Paper presented at the Annual Meeting of the National Association of Research in Science Teaching.

Stanley, H.E., *Beauty and Fractals.* (1992). Plenary Talk at the Symposium on Aesthetics and Science, Boston University Center for the History and Philosophy of Science.

Stanley, H.E., *Beauty and the Fractal.* (1993, February). Plenary Talk, Public Science Day, at the Annual Meeting of the American Association for the Advancement of Science. Boston.

Stanley, H.E, Brecher, K., Buldyrev, S.B., Caserta, F. Garik, P., Glotzer S.C.,Huber, G., Peng, C.K., Prakash, S., Selinger, R.L.B., Shore, L.S., Shann, M.H., Stauffer, D., Taylor, E.F., Trunfio, P., & Ziterman, R. (1993, February). *On Growth and Form: Learning Concepts of Probability & Fractals by Doing Science.* Opening Address at the Annual Meeting of the American Association for the Advancement of Science. Boston.

Trunfio, P. (1995, March). *On Growth and Form: Learning Concepts of Probability and Fractals by Doing Science.* Final project report submitted to the National Science Foundation on Grant Numbers: MDR-8955041 and MDR-9112300. Boston: Boston University Center for Polymer Studies.

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